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ESTIMATION OF TRANSMISSION LINE PARAMETERS USING LINEAR METHOD WITH SYNCHRONIZED AND UNSYNCHRONIZED DATA

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ESTIMATION OF TRANSMISSION LINE PARAMETERS USING LINEAR METHOD WITH SYNCHRONIZED AND UNSYNCHRONIZED DATA

DISSERTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the College of Engineering at University of Kentucky

By

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Lexington, Kentucky

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Lexington, Kentucky

2018

ABSTRACT OF DISSERTATION

ESTIMATION OF TRANSMISSION LINE PARAMETERS USING LINEAR METHOD WITH SYNCHRONIZED AND UNSYNCHRONIZED DATA

Accurate value of transmission line parameters is important for power system protection applications, especially for distance relays whose zone settings are based on positive sequence line impedance. The research is devoted to estimating transmission line positive-sequence parameters from synchronized or unsynchronized measurements of voltage and current phasors that are obtained at both terminals of the line. The positive sequence parameters including series impedance and shunt admittance can be linearly estimated. The linear least square algorithm has been derived in this dissertation for different transmission line configurations. The algorithm is able to handle both synchronized and unsynchronized measurements and deal with potential synchronization errors by explicitly modeling the synchronization angle. Sample results are reported to demonstrate the effectiveness of the proposed method.

Three types of transmission line models depending on line length (long, medium and short) are studied in this dissertation. Chapter 3 uses unsynchronized data for the long transmission line. The derived method can detect the unsynchronized angle and estimate the positive sequence of long line parameters. The proposed method is examined with negative impacts such as errors on currents and voltages data. These errors are added randomly to one set each time to test the robustness of the developed algorithm.

The medium transmission line algorithm derivation is presented in chapter 4. This chapter uses a linear least square to estimate the lumped parameters of a medium transmission line. The two different transmission line circuits are used to model the medium line. The first circuit is a single transmission line with two nodes and is used to evaluate the developed algorithm. The second circuit is a double transmission line. These two lines can have the same or different line parameters or line length. The developed algorithm shows that the proposed method achieves highly accurate results for the estimation of positive sequence line parameters.

The short transmission line is studied in chapter 5. The short transmission line uses less data than the long or medium lines because in this model the shunt capacitance is omitted. Thus, the linear estimation yields highly accurate results. Case studies are considered to test the robustness of this developed method.

The line temperature mainly affects the series resistance, and the developed algorithms in previous three chapters can accurately estimate the transmission line parameters. To simplify the real-time estimation of line resistance and temperature, the series inductance, and shunt capacitance can be treated as constant and known values. Chapter 6 provides such studies of estimating resistance by treating inductance and capacitance as known values.

KEYWORDS: Transmission Line Parameters, Long Transmission Line, Short Transmission Line, Medium Transmission Line, Estimation of Line Parameters, Temperature Affect.

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Date

This Dissertation is dedicated to my parents, my wife, family, brothers and sisters, my friends and to all who taught me.

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Chapter 1

Introduction

This chapter presents a brief introduction about the transmission line, PMUs data and state estimation. The rest of the chapter describes the dissertation outlines.

1.1 Introduction

The transmission line system is used to transmit electricity from one end of the line to another reliably and efficiently. The transmission line is usually characterized by the line parameters including series resistance, series inductance, shunt capacitance, and shunt conductance. Shunt conductance is usually very small and is thus neglected in this research. These parameters play key roles in many power system applications, such as power system analysis and fault location. The power system protection depends on these parameters to locate the line fault or to determine the fault type. Figure 1 shows the electrical power system [1].

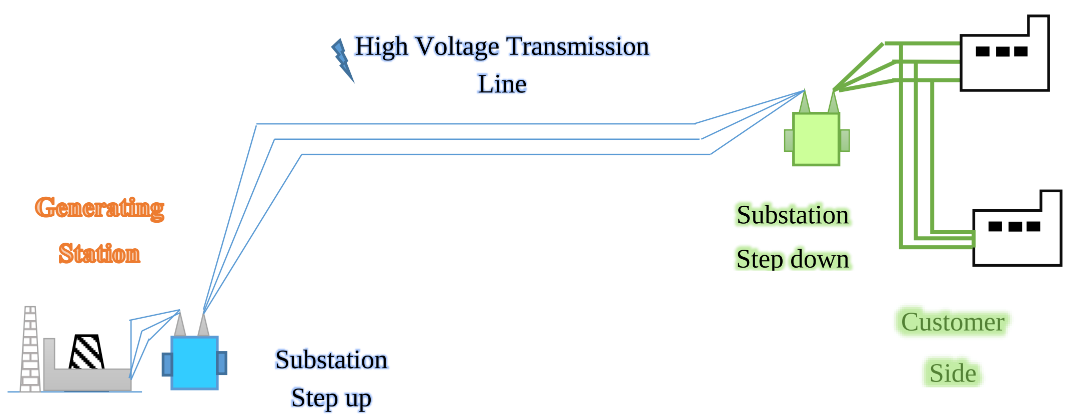

Figure 1-1 Electrical Power System, Transmission Line in Blue

There are three types of transmission lines:

- **Overhead Lines**: the overhead lines usually carry very high voltage, between 100 kV up to 800 kV, and are utilized for the majority of long-distance transmission. These lines require very high voltage to minimize power losses over long distances.
- **Underground Lines:** this type of transmission line is usually used in populated areas, underwater and anywhere that the overhead lines cannot be used. This type is less common than overhead lines due to higher cost and heat-related losses.
- **Subtransmission Lines:** this line carries a lower voltage range (26 to 69 kV) to distribution stations, and can be either overhead or underground transmission lines.

The transmission power system contains many different devices that connect to power lines to ensure that electricity is delivered in an efficient way [2].

1.2 Transmission Line Representation

The transmission line is characterized by four line parameters. The general equations of the voltage and current are related to these parameters. The line parameters can be lumped or uniformly distributed along the line depending on the line length. Regarding the former, lumped parameters provide high accuracy representation of short and medium line lengths. However, if the overhead transmission line is classified as short, then the shunt susceptance can be omitted with little loss of accuracy, and so, series resistance and series inductance along the line will be the only parameters considered.

A medium line length distributed PI circuit is represented by both series resistance and inductance as lumped parameters as well as the shunt branch presented by half of the total capacitance at each end of the line. Shunt conductance is usually neglected in overhead lines.

1.2.1 Short Transmission Line

A transmission line with a length of less than 80 km is considered a short transmission line. In short lines, the shunt susceptance is omitted because of small current leakage; the other line parameters are lumped parameters as shown in figure 1-2.

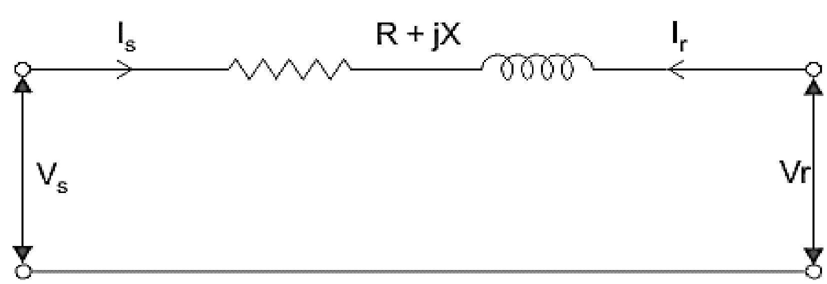

Figure 1-2 Short Transmission Line Diagram

1.2.2 Medium Transmission Lin

A medium transmission line is a transmission line which has a length between 80 and 250 km. The line parameters such as resistance, inductance, and capacitance are uniformly distributed along the line. In medium line length, charging current cannot be omitted, and due to the length of the line, the shunt susceptance plays a significant role in the calculation of exact transmission line parameters.

The shunt capacitance, series resistance, and series inductance are considered as a lumped parameter of the medium transmission line. The medium transmission line is shown below in figure 1-3.

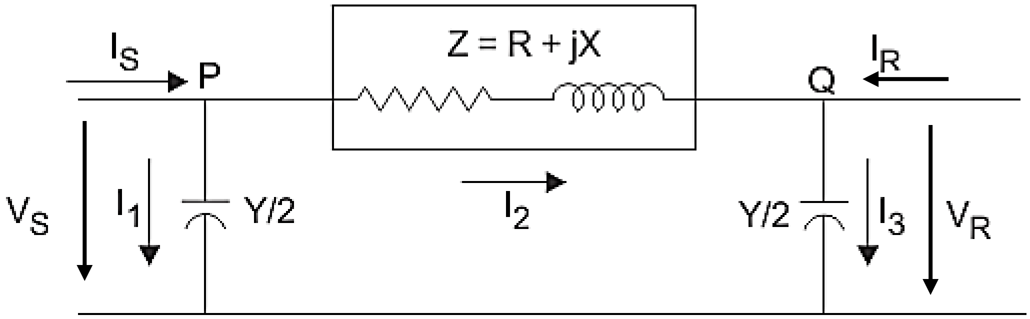

Figure 1-3 Nominal PI of Medium Transmission Line

1.2.3 Long Transmission Line

A line length over 250 km is referred to a long transmission line. The long transmission line must consider the fact that the line parameters are not lumped parameters but, are uniformly distributed throughout the length of the line.

A long transmission line must be considered as divided into various sections, and each section consists of resistance, inductance, and capacitance as shown below in figure 1-4.

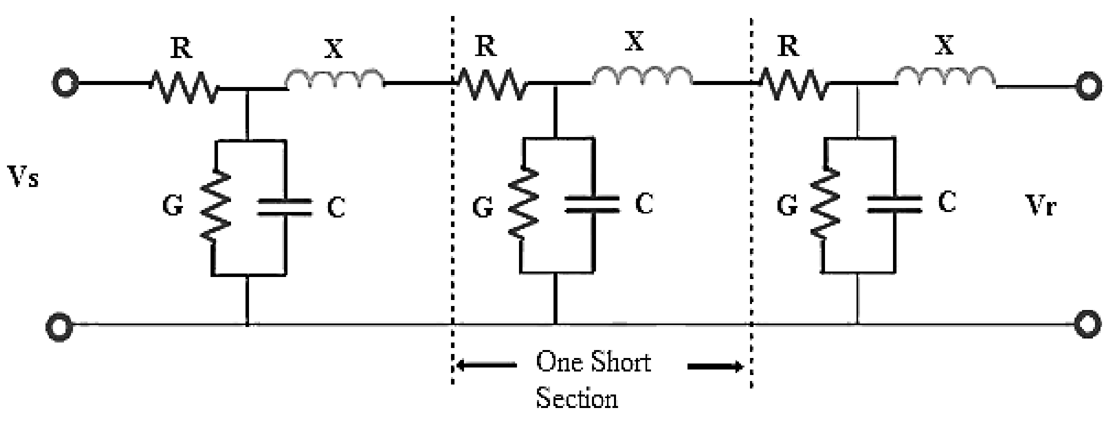

Figure 1-4 Long Transmission Line Showing Distributed Parameters

A long transmission line can also be represented by a circuit called equivalent nominal PI. This equivalent PI circuit is different from nominal PI for medium transmission lines. The equivalent circuit is only convenient for representing the actual long transmission line during the analysis. For the load flow and transmission line studies, this equivalent PI circuit is highly helpful without losing any accuracy in the calculations. The parameters in the equivalent circuit are represented by hyperbolic functions [2].

The total series impedance of the line is represented by Z', and the shunt element is represented by Y' as modeled in figure 1-5.

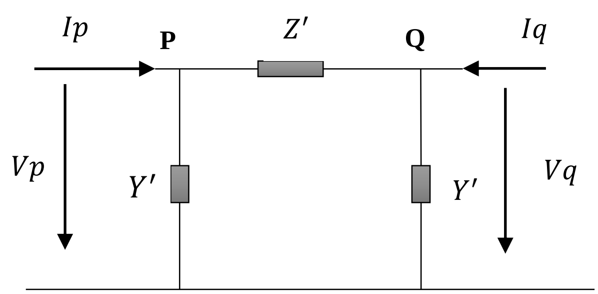

Figure 1-5 Equivalent PI Circuit for Long Transmission Line

1.3 Phasor Measurement Unit

The phasor measurement unit (PMU) is a device that can measure the magnitude and angle of voltages and currents at a different location with stamped time. The PMU's data is highly helpful for studying the power system analysis. The data from other measurement devices like supervisory control and data acquisition (SCADA) cannot provide a phase angle, which has become more important for power system analysis. The PMU device can provide digital phasor measurements for the voltage and current at the installed location. The PMU usually measures the positive sequence of the phase magnitude and phase angle of the alternate current (AC) waveform with high measurement accuracy. The magnitudes and phase angles obtained at multiple locations can be synchronized to a common time source. The Global Position Satellite (GPS) has the ability to give the synchronized timing source with at least sampling time of 10 microsecond, which means the PMU can provide the voltage and current measurements with high accuracy [3].

For multiple sets of measurements, the synchronization of the time is achieved by a precise time attached to every measurement record. The clock is used to stamp time to each set of the measurement. The clock is augmented to the Global Positioning System (GPS) in order to ensure its precision.

Figure 1-6 shows the schematic of the PMU. The PMU is connected to the secondary windings of potential and current transformers. These transformers provide analog readings as an input to the anti-aliasing filter, and this filter is used to mitigate the frequencies that are higher than Nyquist frequency.

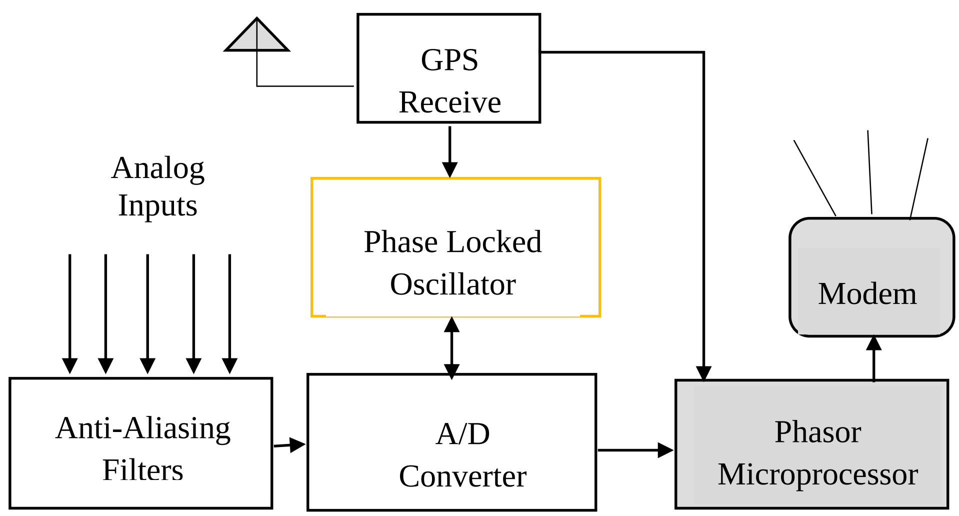

Figure 1-6 Phasor Measurement Unit Block Diagram

The phase locked oscillator is the device that locks the sampling rate with the GPS clock. Then the A/D converter converts the analog signals (voltage and current) to digital signals. Then microprocessor applies the digital signal into the Discrete Fourier Transform. The microprocessor estimates the magnitude and angle of both voltages and currents then transmit them to the modem [4]. Figure 1-7 shows discrete Fourier transformer that used to extract the phasor measurements for the current and voltage in Matlab.

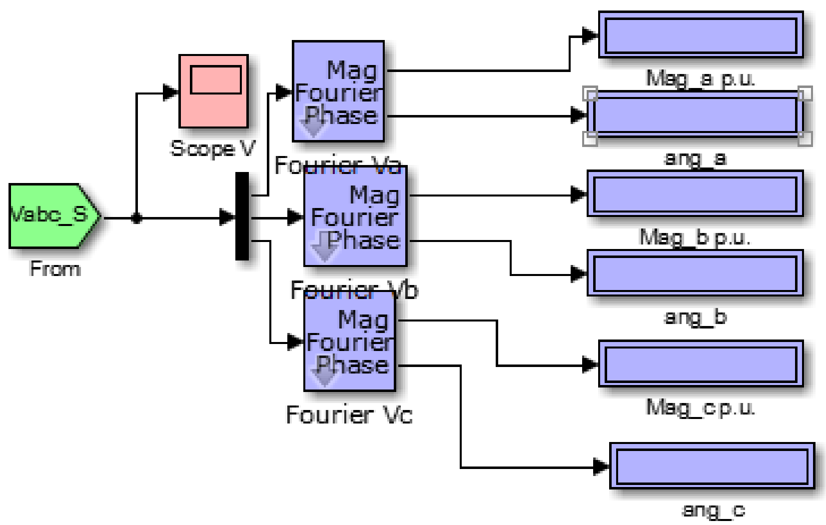

Figure 1-7 Simulink Model of measurement Function

1.4 State Estimation

The state estimation is a widely used tool in power systems. It is essentially a technique that is used to find the unknown variable of the state values based on limited measurements. The state estimation theory and ideas were applied and introduced into the power system by MIT's professor Fred Schweppe in 1969. He defined the state estimator as "a data processing algorithm for converting redundant meter readings and other available information into an estimate of the state of an electric power system." Since then, it has been widely applied in the energy control centers (ECCs) of electric utilities and independent system operators (ISOs). Today, state estimation is an essential part of almost every energy management system throughout the world [5]. In order for the control center of a power system to maintain the reliable and secure deliverance of power to the customer, it requires a real-time state estimation tool that works simultaneously with other power systems devices.

1.4.1 Non-Linear System

The non-linear least square can estimate more unknown parameters using less relatively known data sets. The non-linear method uses the iterative optimization technique to estimate the unknown parameters, which is usually time-consuming. The accuracy of this method depends on the starting point. The non-linear method requires a starting point for the unknown parameters before it starts the iterative calculation. These values should be closer to the real values of the unknown parameter in order for the program to converge.

1.4.2 Linear System

Linear least square method minimizes the deviation of the squares between the known data and the model. This method widely used because of its effectiveness. Also, this method easy to implement, understand and interpret for different types of systems. Furthermore, the least square method usually produces the optimal estimation of the unknown values this makes it more sensitive to the accuracy of the known data that may contain errors or significant points that are used for the fitting the model [6].

1.5 Dissertation Outline

The remainder of this dissertation is organized as follows: The literature review related to the state estimation and methods to estimate the transmission line in Chapter 2. The method of estimating the positive sequence of the long transmission line parameters presented in Chapter 3. Chapter 4 shows the proposed method for estimating the medium transmission line using a linear method. The linear method for estimating the positive sequence of the short transmission line is discussed in Chapter 5. The temperature effect on transmission lines medium and short is discussed in Chapter 6. Chapter 7 concludes the dissertation.

Chapter 2

2.1 Literate review

Real-time estimation of power transmission line parameters has become possible with the availability of synchronized and unsynchronized measurements of voltage and current. The penetration of renewable energy sources such as wind and solar power become attractive complementary resources and the backbone of many economies worldwide. For this reason, the reliable and efficient operation of the power system networks is a crucial challenge because of the issues related to fluctuating power flows and reliability. One of the critical aspects is the consideration of the transmission line parameters such as the series resistance and reactance. The transmission line parameters play a key role in the protection and control of the power system [7].

Power system research required for accurately estimating transmission line parameters, including series resistance, series reactance and shunt susceptance. These estimated parameters required for power protection relay settings, power flow analysis, and fault location [8].

The protection relays are essential devices protecting the power systems to maintain the reliability and operating safety of power networks. There are two types of relays: overcurrent and distance (impedance) relay. In general, the impedance relay is more sensitive to line parameters. The concept of operating overcurrent relays is to monitor the current through the line and trip the breaker when the current exceeds the limit value. Engineers select the settings of the relays depending on maximum load and minimum fault current through the line segment. The calculation of the currents' values depends on the transmission line's phase or sequence of the line impedance. The accuracy of tripping the circuit breaker depends on the transmission line parameters; inaccurate transmission line parameters can cause improper operation of the overcurrent relays. The distance relay has a different operation concept than the protection relays. The main idea of the distance relay is to monitor the ratio between the voltage and current measurements provided by the measurement system and to calculate that ratio. The calculated ratio presents the impedance seen by the relay, and this impedance is compared to the stored impedance in the settings of the relay. If the calculated value falls under the sets of the threshold, the relay trips a circuit breaker and isolates the fault zone [9].

There are two methods to calculate the transmission line parameters. These methods are theoretical calculation and state estimation. The theoretical method depends on the physical properties of line conductors, tower configuration and the environment in which the line is operating to calculate the line parameters. Some factors must be taken into account during this calculation such as the resistance affected by ambient temperature, conductor properties, conductor spiraling, and operating frequency. The inductance is influenced by the spacing between the conductors, line transposition, conductor bundling, and the conductor standers. The capacitance is the electrical field which is influenced by the space between the conductors, conductor bundling and in some cases the effect of the earth is considered [10].

The state estimation has a different way to calculate the line parameters. The state estimation usually uses the available data such as SCADA or PMU data. Due to many new technologies accessing the power system, the PMU's have become more popular and available tool in the power system. The state estimation has several advantages over the theoretical method to compute the line parameters. The conductor properties and tower configuration are significant factors that influence the parameters in theoretical calculation. However, they do not have to be known in the state estimation, and the state estimation utilizes the PMU's data when the data are available. That means the method re-estimates the line parameters each time it receives new data. These updated parameter values can be updated across the various applications that use them to reflect the changing conditions of transmission network usage [11].

Several approaches for estimating the line parameters from measured data were implemented to the power system analysis. References [2] [12]are using the traditional manner to estimate the line parameters, employing factors including a conductor type, conductor geometry, and tower parameters. These factors deviate from the actual values, and this deviation most likely will lead to error in estimating the line parameters.

The improvement of estimating the line parameters is done by using several algorithms. Most of the algorithms use non-linear methods which use the Newton Raphson method. The Newton Raphson method provides highly accurate results for estimating the line parameters. However, it is time-consuming and takes time to converge. In order to get the high accurate results a good starting point is required.

The primary source of the data for the transmission line is the PMUs or supervisory control and data acquisition system (SCADA). The SCADA does not provide the phasor measurements, and less precision on real-time data can lead to low precision using the state estimation. PMU gives the precise and accurate real-time measurements for the currents and voltages. The PMU has the ability to help and show the synchronization signal through the GPS technology. The PMU has a better capability of giving precise measurements for the transmission line, and it is more efficient for the power system because it has a sampling time of milliseconds [13].

The author of [14], is using the state estimation to estimate the positive sequence of the line parameters using the equivalent PI circuit. The unknown parameters are arranged to be non-linearly dependent with the known measurements,

The estimation of transmission line parameters using the non-linear method using PMU measurements has been done in the past as in [15]. The estimated parameters depend on the system’s frequency; the proposed algorithm estimates the positive sequence line parameters at the fundamental frequency, which is the most widely implemented technique in power system applications. The author of [15] uses the non- linear recursive method by implementing the non-linear least square. The other way to estimate the line parameters yields in [16].

The Ref [17] uses the non-linear state estimation, distributed circuit, and the transmission line assumed to be compensated. The algorithm developed in that paper called an on-line optimal estimation method, which utilizes the voltages and currents from the two terminals of the transmission line. The author of [17]is also considering the impact of negative measurements due to various reasons such as synchronization errors or whether abnormality operation can be detected and successfully identified.

The optimal estimator for on-line parameter estimation is presented in [18]. The proposed approach estimated the positive sequence parameters during normal operation. The accuracy of this method is enhanced by detecting and removing bad measurements. It also considers removing the synchronization errors that may occur.

A method for online estimation of the parameters of the untransposed three phases single circuit and untransposed two parallel transmission lines using synchronous voltages and currents at both ends of the line is proposed in [12]. Model decomposition is applied to transform two parallel lines into double independent three phase circuits.

Many studies done in the past used the nonlinear method, which is basically using the Newton Raphson iteration algorithm. The accuracy of these methods depends on the measurements reading, due to renewable energy penetrating the new power system network requiring high and new algorithms that can work online and with less time consumed. Most related studies are done with using the non-linear methods.

As mentioned in [19] [20], it is more beneficial if the estimation of the line parameters approach has the ability to identify and detect the measurement errors as well as the unsynchronization accuracy. Since the bad data would be detected, only the proper data is exploited to achieve the more accurate estimation of the line parameters. Similarly, when the synchronization accuracy is detected, that leads us to avoid synchronization assumption inaccuracy.

The double circuit transmission lines are extensively used by utilities for bulk transfer of power because of reliability, right of way and economic considerations. The author of [21] is estimating the double circuit of transmission positive sequence line parameters based on PMU’s data.

The methods for estimating the transmission line parameters are widely used for the power system. These methods depend on the line length, and whether the line is transposed or untransposed. The author of [22] is using the PMU's data to estimate the line parameters for fully transposed transmission line based on the synchronized measurements for the voltage and current. The estimation of untransposed transmission line parameters has been studied in [23]. The author is using the untransposed transmission line to evaluate all his case studies, with all results in that paper based on the extended Kalman filter, which is using the non-linear method. The Kalman filter is used to track the line parameter iteratively.

The non-linear algorithm is used to estimate the line parameters. The authors of [24] are using the estimated line resistance to determine the actual value of the ambient temperature using the unique thermal formula. The ambient temperature changes, thus the resistance only affected by that changes. The benefit in estimating the ambient temperature is to determine the line sag.

The non-iterative method for estimating the line parameters presented in [25], the method presented is utilizing the pre-fault measurements; the authors are using the synchronized voltages and currents data. The method is relying on the voltage and current during the pre-fault measurements. All derived equations are simplified to be linearly solved. This method also can be useful for the wide area monitoring or protection relays.

Estimation of the positive sequence of the transmission line has been done in a couple of studies. This paper [26] is presenting non-linear to estimate the zero sequence of the line parameters. This method requires unbalanced system or during grounded fault measurements, and the system has to be at least two nodes three line or three nodes. The method shows good results and estimation. This method has been done experimentally, so it is more reliable and usable.

Chapter 3

Estimation of Line Parameters Using Long Transmission Line Model

3.1 Introduction

The line length plays a key role in the estimation of transmission line parameters. A transmission line length of 250 km and up is considered as a long transmission line and to get the high accuracy of calculating the line parameters, the line circuit represented by an equivalent PI circuit, not as a lumped circuit. The fact is that in a long transmission line, the line parameters are distributed uniformly throughout the line rather than lumped.

This chapter devoted to estimate the positive-sequence parameters of the transmission line using unsynchronized measurements of voltage and current phasors that obtained at both terminals. The series impedance and shunt admittance parameters can be linearly estimated using the algorithm developed in this chapter. The algorithm is developed based on the distributed parameter line model; the line is assumed to be transposed. The approach developed in this chapter is considered as a linear method, and the linear least square method is used to estimate the positive-sequence line parameters. The method is also applicable when perfect synchronized measurements obtained by Phasor Measurement Unit, also able to deal with potential synchronization errors by explicitly modeling the synchronization angle.

The appropriate results for line parameters estimation depend on the exact circuit of the line. The series impedance and shunt susceptance calculated by solving the differential equations; where voltages and currents measurements are represented as a function of line length, these differential equations are described by hyperbolic forms.

A long transmission line is assumed to operate under certain conditions to obtain better estimation results

- The transmission line is operated under sinusoidal, steady-state and balanced three-phase conditions.
- The transmission line is assumed to be transposed along the line.
- Shunt conductance is omitted

The remainder of this chapter is organized as follows: section 3.2 shows the derivation of the proposed method based on single circuit distributed equivalent PI of the long transmission line. Section 3.3 shows the derivation of the proposed method when the double circuit of the transmission line is used. The results with discussion are presented in section 3.4. The conclusion is presented in section 3.5.

3.2 Proposed Method for Single Circuit Long Transmission Line

Figure 3.1 shows a single circuit of the long transmission line; represented by the equivalent PI circuit; the line is transposed between p and q terminals, where these two nodes are considered as Thevenin equivalent sources. The proposed method utilizes the steady-state voltages and currents measurements taken in different time sectors. Figure 3.1 shows the equivalent PI circuit based on the distributed parameters model. This model is employed for the derivation of the proposed method.

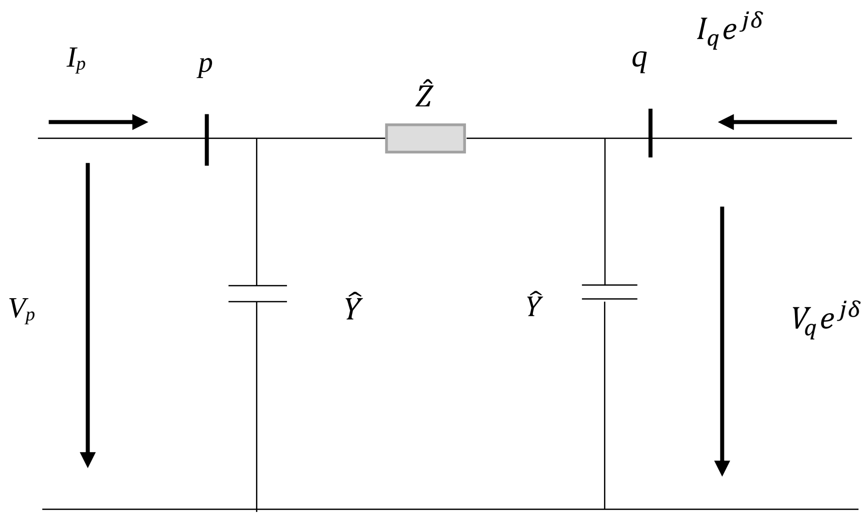

Figure 3-1Equivalent PI circuit of Long Transmission Line

The following notations are used for this chapter:

V_p , V_q : The positive sequence voltage phasors at two terminals p and q.

I_p and I_q : The positive sequence current phasors at two terminals p and q.

Z: The positive-sequence series impedance per unit of length.

Y: The positive-sequence shunt susceptance per unit of length.

$\hat{Z}$: The equivalent series impedance of the long line segment.

$\hat{Y}$: The equivalent shunt admittance of the long line segment.

Zc : The characteristic impedance of the line.

γ : The propagation constant.

δ : The unsynchronization angle.

l : The line length.

In deriving the method, unsynchronized measurements are utilized. It is evident that the method is also applicable if the synchronized measurements are used, the method can deal with any possible unsynchronization error by introducing variable δ . According to Figure 3.1, the transmission line equivalent circuit parameters can be expressed as

$$\hat{Z} = Zc\ sinh(\gamma l) \tag{3.1}$$

$$\hat{Y} = \ tanh(\gamma l/2)/Zc \tag{3.2}$$

Now the terminal currents can be written as follows:

$$I_p = \left(\hat{Y} + (1/\hat{Z})\right)V_p - (1/\hat{Z})V_q\ e^{j\delta} \tag{3.3}$$

$$I_q e^{j\delta} \ = \left(\hat{Y} + (1/\hat{Z})\right)V_q\ e^{j\delta} - (1/\hat{Z})V_p \tag{3.4}$$

Eq. (3.3) and (3.4) can be augmented together as:

$$\begin{bmatrix} I_p \\ I_q e^{j\delta} \end{bmatrix} = \begin{bmatrix} \left(\hat{Y} + (1/\hat{Z})\right) & (-1/\hat{Z}) \\ (-1/\hat{Z}) & \left(\hat{Y} + (1/\hat{Z})\right) \end{bmatrix} \begin{bmatrix} V_p \\ V_q\ e^{j\delta} \end{bmatrix} \tag{3.5}$$

Using these new relations

$$\text{A=}\left(\hat{Y} + (1/\hat{Z})\right) \tag{3.6}$$

$$B = -1/\ \hat{Z} \tag{3.7}$$

By substituting the relations in Eq (3.6) and (3.7) into (3.5) leads to

$$\begin{bmatrix} I_p \\ I_q e^{j\delta} \end{bmatrix} = \begin{bmatrix} A & B \\ B & A \end{bmatrix} \begin{bmatrix} V_p \\ V_q\ e^{j\delta} \end{bmatrix} \tag{3.8}$$

The unsynchronized angle is unknown, and the known quantities are $[Vp, Ip, Vq, Iq\ ]$. Rearranging (3.8) gives

$$I_q = A\, V_q + B\, e^{-j\delta}\; V_p \tag{3.9}$$

From (3.8) and (3.9), the two new unknown parameters can be defined as follows, by using the aforementioned relations

$$C = B\, e^{j\delta} \tag{3.10}$$

$$D = B\, e^{-j\delta} \tag{3.11}$$

Rewrite (3.8) and (3.9) in terms of new unknown variables relations

$$\begin{bmatrix} I_p \\ I_q \end{bmatrix} = \begin{bmatrix} A & C \\ D & A \end{bmatrix} \begin{bmatrix} V_p \\ V_q \end{bmatrix} \tag{3.12}$$

Equation (3.12) can be rearranged in terms of three unknown parameters and multiple sets of measurements

$$X = \begin{bmatrix} A \\ C \\ D \end{bmatrix} \tag{3.13}$$

Since there are three unknown variables, at least two sets of measurements are required. The two equations can be expanded to any available set of measurements. The first and second sets of measurement are shown below

$$\begin{aligned} I_{p1} &= A\, V_{p1} + CV_{q1} + 0 * D \\ I_{q1} &= A\, V_{q1} + 0 * C + D\, V_{p1} \end{aligned} \tag{3.14}$$

$$\begin{aligned} I_{p2} &= A\, V_{p2} + CV_{q2} + 0 * D \\ I_{q2} &= A\, V_{q2} + 0 * C + D\, V_{p2} \end{aligned} \tag{3.15}$$

Eq. (3.14) and (3.15) can be rewritten in terms of the three unknown variables and however many known sets of measurements as

$$\begin{bmatrix} I_{p1} \\ I_{q1} \\ I_{p2} \\ I_{q2} \end{bmatrix} = \begin{bmatrix} V_{p1} & V_{q1} & 0 \\ V_{q1} & 0 & V_{p1} \\ V_{p2} & V_{q2} & 0 \\ V_{q2} & 0 & V_{p2} \end{bmatrix} \begin{bmatrix} A \\ C \\ D \end{bmatrix} \tag{3.16}$$

The unknown variables can be obtained by using the linear least squares method as shown below:

$$U = H\ X \tag{3.17}$$

Where H is composed of two end voltages, U the current vector, and X the unknown variable vector. The solution to (3.18) is

$$X = (H^T\ H)^{-1}\ (H^T\ U) \tag{3.18}$$

Then the three unknown variables are derived as follows:

$$A = (\hat{Y} + (1/\hat{Z})) \tag{3.19}$$

$$C = (-1/\hat{Z})\ e^{j\delta} \tag{3.20}$$

$$D = (-1/\hat{Z})\ e^{-j\delta} \tag{3.21}$$

The unsynchronization angle can be calculated as

$$e^{j\delta} = \sqrt{C/D} \tag{3.22}$$

The series branch can be found by using either (3.20) or (3.21). The shunt branch can be found based on (3.19). Referring to (3.1) and (3.2) where the hyperbolic functions are defined in exponential form as

$$\sinh(\gamma l) = \frac{e^{\gamma l} - e^{-\gamma l}}{2} \tag{3.23}$$

$$\tanh(\gamma l) = \frac{e^{\gamma l} - e^{-\gamma l}}{e^{\gamma l} + e^{-\gamma l}} \tag{3.24}$$

The characteristic impedance can be calculated as

$$Zc = \hat{Z}/(\sinh(\gamma l)) \tag{3.25}$$

Alternatively, from equation (3.2), the characteristic impedance is computed as

$$Zc = (\tanh(\gamma l/2))/\hat{Y} \tag{3.26}$$

The two equations (3.25) and (3.26) represent the characteristic impedance by the series impedance and shunt admittance, respectively. Now the only unknown variable is the propagation constant γ

$$(\tanh(\gamma l/2))/\hat{Y} \ = \hat{Z}/\sinh(\gamma l) \tag{3.27}$$

$$\sinh(\gamma l) * \tanh(\gamma l/2) = \hat{Y}\hat{Z} \tag{3.28}$$

By substituting the hyperbolic function into the equation (3.28)

$$\frac{e^{\gamma l} - e^{-\gamma l}}{2} * \frac{e^{\gamma l/2} - e^{-\gamma l/2}}{e^{\gamma l/2} + e^{-\gamma l/2}} \ = Y\ Z \tag{3.29}$$

Equation (3.29) will be rearranged as a quadratic equation and solving it will yield the propagation constant as follows

$$e^{2\gamma l} - (2Y^{\sim}\ Z^{\sim} + 2)e^{\gamma l} + 1 = 0 \tag{3.30}$$

Denote $f = e^{\gamma l}$, which is calculated from (3.30), and then the propagation constant is obtained as

$$\gamma = \frac{1}{l}\ln(f) \tag{3.31}$$

The characteristic impedance and propagation constant are determined by

$$Zc = \sqrt{z/y} \tag{3.32}$$

$$\gamma = \sqrt{z * y} \tag{3.33}$$

By using (35) and (36), the series resistance and series reactance per unit length are obtained as

$$\begin{aligned} \text{Series Resistance} &= \text{real}(\text{Zc}\,\gamma) \\ \text{Series Reactance} &= \text{imag}(\text{Zc}\,\gamma) \end{aligned} \tag{3.34}$$

The shunt susceptance per unit length is calculated by

$$\text{Shunt Susceptance} = (\gamma/\text{Zc}) \tag{3.35}$$

3.3 Proposed Method for Double Circuit Long Transmission Line

3.3.1 Using the Three node Voltages

Following the same procedure as in network 3.2, the transmission line shown in figure 3.2 has three nodes P_1, P_2 and P_3, where each is considered as a Thevenin equivalent source with two single lines sharing the same bus at P_3. The transmission lines 1 and 2 are considered as transposed lines, and each one has different parameters and different length.

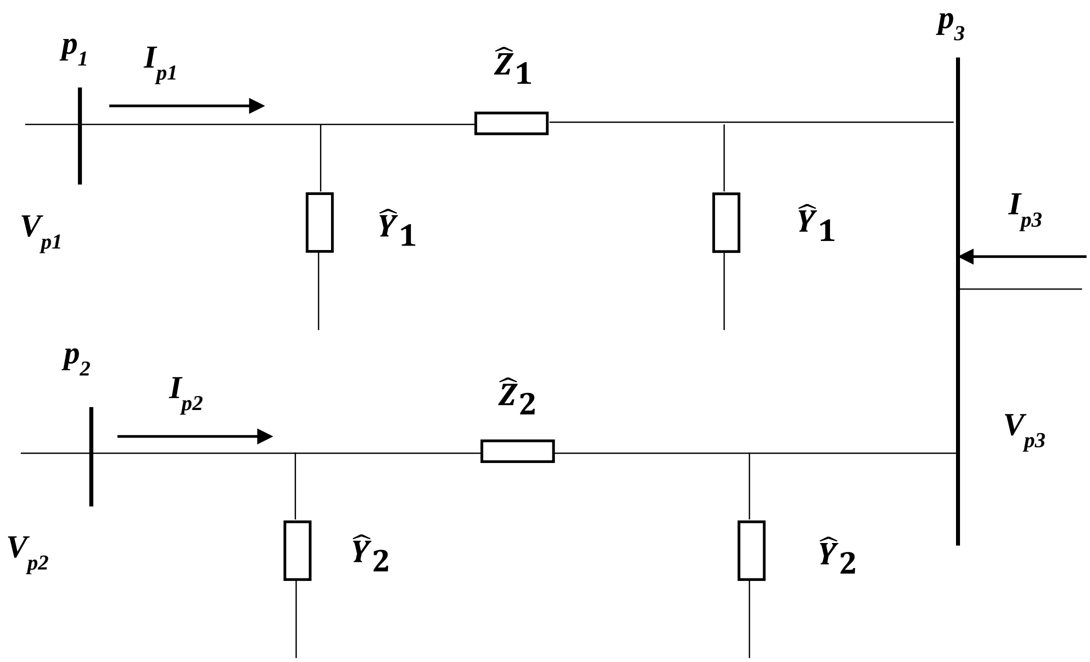

Figure 3-2 Equivalent PI Double circuit of Long Transmission Line

Referring to figure 2 and utilizing synchrophasors equation at bus 3, for the first line we can acquire the voltage as

$$V_{p3} = V_{p1} - \left(I_{p1} - \hat{Y}_1 V_{p1}\right)\hat{Z}_1 \tag{3.36}$$

The node p_3 voltage interims of the node p_2 can be obtained as follows

$$V_{p3} = V_{p2} - \left(I_{p2} - \hat{Y}_2 V_{p2}\right)\hat{Z}_2 \tag{3.37}$$

Since the known variables are $[V_{p3}, V_{p2}, V_{p1}, I_{p1}, I_{p2}]$ and the unknown variables are $[\hat{Z}_2, \hat{Y}_2, \hat{Z}_1, \hat{Y}_1]$, the equations (3.36) and (3.37) can be rewritten in terms of the four unknown variables as follows:

$$V_{p3} = V_{p1} - \hat{Z}_1 I_{p1} + \hat{Z}_1 \hat{Y}_1 V_{p1} \tag{3.38}$$

$$V_{p3} = V_{p2} - \hat{Z}_2\, I_{p2} + \hat{Z}_2\hat{Y}_2 V_{p2} \tag{3.39}$$

Rearranging the previous two equations as

$$V_{p3} = V_{p1}(1 + \hat{Z}_1\hat{Y}_1) - \hat{Z}_1\, I_{p1} \tag{3.40}$$

$$V_{p3} = V_{p2}(1 + \hat{Z}_2\hat{Y}_2) - \hat{Z}_2\, I_{p2} \tag{3.41}$$

The equations (3.40) and (3.41) are augmented together based on the unknown variables, and as $i^{th} = 1, 2, \ldots\ldots, N$; with N being the total number of measurement sets, it shows as:

$$\begin{bmatrix} V_{p3i} \\ V_{p3i} \end{bmatrix} = \begin{bmatrix} V_{p1i} & I_{p1i} & 0 & 0 \\ 0 & 0 & V_{p2i} & I_{p2i} \end{bmatrix} \begin{bmatrix} \left(1 + \hat{Z}_1\hat{Y}_1\right) \\ \hat{Z}_1 \\ \left(1 + \hat{Z}_2\hat{Y}_2\right) \\ \hat{Z}_2 \end{bmatrix} \tag{3.42}$$

The unknown variables can be estimated using the linear least square method. By using the equation (3.17), where H is the composed matrix of voltages and currents at terminals P_1 and P_2, U is the voltage measurements at terminal 3, and the X vector is an unknown variable for both lines.

Where X vector is defined as

$$X = \begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix} \tag{3.43}$$

The unknown variables are given by

$$A = \left(1 + \hat{Z}_1\hat{Y}_1\right) \tag{3.44}$$

$$B = \hat{Z}_1 \tag{3.45}$$

$$C = \left(1 + \hat{Z}_2\hat{Y}_2\right) \tag{3.46}$$

$$D = \hat{Z}_2 \tag{3.47}$$

The equations (3.44) and (3.45) are presenting the first line parameters and equations (3.46) and (3.47) are presenting the second line parameters. By following the same procedures in the first proposed method. The linear least square method solution equation shown as follows:

$$X = (H^T\ H)^{-1}\ (H^T\ U) \tag{3.48}$$

The four unknown variables are obtained by solving the linear least square equation (3.48), and by applying equations from (3.25) to (3.35) for each transmission line the series impedance, series inductance, and shunt capacitance can be estimated.

3.3.2 Using Two node Voltages

Following the same procedure in network 3.3.1 and using the same long transmission model showing in figure 3-2. With the three nodes P_1, P_2 and P_3, where each end is considered as a source, and two single lines P_1 and P_2 are sharing the same bus at P_3. The transmission lines 1 and 2 are considered as transposed lines and operate at normal conditions.

The idea here is to use less data than the previous method. I am trying to eliminate the voltage at bus P_3, the only data that is required for this estimation method are the voltages and currents at P_1 and P_2 terminals.

Referring to figure (3-2), utilizing synchrophasors data at bus 3, we can acquire:

$$V_{p3} = V_{p1} - \left(I_{p1} - \hat{Y}_1 V_{p1}\right)\hat{Z}_1 \tag{3.49}$$

$$V_{p3} = V_{p2} - \left(I_{p2} - \hat{Y}_2 V_{p2}\right)\hat{Z}_2 \tag{3.50}$$

Since the known variables are $[V_{p2}, V_{p1}, I_{p1}, I_{p2}]$, and the unknown variables are $[\hat{Y}_2, \hat{Z}_2, \hat{Z}_1, \hat{Y}_1]$; and by eliminating the intermediate variable *Vp3* the equations (3.49) and (3.50) can be rewritten in terms of the four unknown variable as follows:

$$V_{p2} - \left(I_{p2} - \hat{Y}_2 V_{p2}\right)\hat{Z}_2 = V_{p1} - \left(I_{p1} - \hat{Y}_1 V_{p1}\right)\hat{Z}_1 \qquad (3.51)$$

Rearranging the previous equation as

$$V_{p1} - V_{p2} = \hat{Z}_2 I_{p2} - \hat{Z}_2 \hat{Y}_2 V_{p2} + \hat{Z}_1 I_{p1} - \hat{Z}_1 \hat{Y}_1 V_{p1} \qquad (3.52)$$

The equation (3.52) can be rewritten based on the unknown variable on the right side, and for multiple sets of measurements as:

$$\begin{bmatrix} V_{p1i} - V_{p2i} \\ . \\ . \\ V_{p1N} - V_{p2N} \end{bmatrix} = \begin{bmatrix} I_{p1i} & -V_{p1i} & -I_{p2i} & V_{p2i} \\ & . & & \\ & . & & \\ I_{p1N} & -V_{p1i} & -I_{p2N} & V_{p2i} \end{bmatrix} * \begin{bmatrix} \hat{Z}_1 \\ \hat{Z}_1\hat{Y}_1 \\ \hat{Z}_2 \\ \hat{Z}_2\hat{Y}_2 \end{bmatrix} \qquad (3.53)$$

Where *X* is defined as

$$X = \begin{bmatrix} \hat{Z}_1 \\ \hat{Z}_1\hat{Y}_1 \\ \hat{Z}_2 \\ \hat{Z}_2\hat{Y}_2 \end{bmatrix} \qquad (3.54)$$

The first two rows in equation (3.54) present the first line parameters and the last two rows present the second line parameters. By following the same procedures from the first proposed method and using the linear least square method, it is possible to solve the equation (3.53).

For each line, we need to follow these equations. The characteristic impedance can be calculated as:

$$Zc = \hat{Z}/(\sinh(\gamma l)) \tag{3.55}$$

Alternatively, the characteristic impedance is computed as

$$Zc = (\tanh(\gamma l/2))/\hat{Y} \tag{3.56}$$

The two equations (3.55) and (3.56) represent the characteristic impedance by the series impedance and shunt admittance, respectively. Now the only unknown variable is the propagation constant γ

$$\sinh(\gamma l) * \tanh(\gamma l/2) = \hat{Y}\hat{Z} \tag{3.57}$$

To solve the equation (3.57), the exponential function must be used to simplify the equation as:

$$\frac{e^{\gamma l} - e^{-\gamma l}}{2} * \frac{e^{\frac{\gamma l}{2}} - e^{-\frac{\gamma l}{2}}}{e^{\frac{\gamma l}{2}} + e^{-\frac{\gamma l}{2}}} = \hat{Y}\hat{Z} \tag{3.58}$$

Rearranging the equation (3.58) as a quadratic equation and solving it will show the propagation constant as follows:

$$e^{2\gamma l} - \left(2\,\hat{Y}\hat{Z} + 2\right)e^{\gamma l} + 1 = 0 \tag{3.59}$$

Interdicting new variable $f = e^{\gamma l}$, where the propagation constant can be calculated as

$$\gamma = \frac{1}{l}\ln(f) \tag{3.60}$$

The equations (3.32) and (3.33) represent the propagation constant and the characteristic impedance. Therefore, the series resistance and series reactance in per unit of length are obtained as

$$\text{Series Resistance} = \text{real}(\text{Zc}\,\gamma) \tag{3.61}$$

$$\text{Series Reactance} = \text{imag}(\text{Zc}\,\gamma) \tag{3.62}$$

The shunt susceptance per unit length is calculated by

$$\text{Shunt Susceptance} = (\gamma/\text{Zc}) \tag{3.63}$$

3.4 Results and Discussion

This section presents the results for the long transmission line, and the results are analyzed to demonstrate the performance and effectiveness of the proposed approach. The two different transmission line models are simulated in Matlab to utilize the proposed method, and the SimPowerSystem tool and Matlab/Simulink are used to construct the proposed transmission lines. These transmission lines are transposed lines based on distributed equivalent circuits.

Per unit system is used in this study based on 500kV base voltage and 1000MVA base power; this per unit system is used throughout the dissertation.

3.4.1 Case 1 (Single Circuit Transmission Line)

This section presents multiple case studies that use the proposed approach for a single circuit of the transmission line. All data are generated by the Matlab simulation. The Matlab Simulation “simpowersystem tool” is applied to represent the long transmission line mentioned in figure (3.1), and, generating the voltage and current phasors by varying the angle between two terminals with unsynchronized phases, to get at least two to four sets of measurement.

All data shown in tables are in per unit, and 300 km of line length is used. The developed algorithm has been implemented in Matlab. The actual values of the positive sequence line parameters are listed below [15].

- Series Resistance

$$R = 6.19303 \times 10^{-4} \text{ p.u./km}$$

- Series inductance

$$L = 1.46432 \times 10^{-3} \text{ p.u./km}$$

- Shunt Capacitance

$$C = 1.14016 \times 10^{-3} \text{ p.u./km}$$

Table 3-1 shows the three sets of measurement and the estimated positive-sequence parameters per unit of length with an unsynchronization angle of (10 degrees). The third column in each table yields the estimated parameter result in P.U, including the unsynchronization angle in “degrees.”

Table 3-1: Estimation results with three sets of measurements

Quantities	Measured values (p.u.)	Estimated Parameters
V_{p1}	0.9325 + j0.3214	
I_{p1}	0.4110 + j0.3636	Series Resistance =
V_{q1}	0.9661 – j0.007448	6.19303e-4 p.u./km
I_{q1}	-0.4842 + j0.06420	
V_{p2}	0.901 + j0.4012	
I_{p2}	0.4379 + j0.4083	Series Reactance =
V_{q2}	0.9556 – j0.05886	1.46432e-3 p.u./km
I_{q2}	-0.5357 – j0.1066	
V_{p3}	0.8865 + j0.4324	Shunt Susceptance = 1.14016e-3 p.u./km
I_{p3}	0.4485 + j 0.4331	
V_{q3}	0.9513 – j0.83870	Unsynchronization
I_{q3}	-0.5771 – j0.1307	Angle=10 degrees

Table 3.2 exhibits the estimation line parameter results with four sets of measurement and an unsynchronization angle of 20 degrees.

Table 3-2: Estimated parameters with four sets of measurements

Quantities	Measured values (p.u.)	Estimated Parameters
V_{p1}	0.9325 + j0.3214	Series Resistance = 6.19303e-4 p.u./km
I_{p1}	0.4110 + j0.3636	
V_{q1}	0.9502 – j0.1751	
I_{q1}	-0.4881 + j0.02081	
V_{p2}	0.9010 + j0.4012	Series Reactance = 1.46431e-3 p.u./km
I_{p2}	0.4379 + j0.4083	
V_{q2}	0.9513 – j0.1079	
I_{q2}	-0.5461 – j0.01210	
V_{p3}	0.8865 + j0.4324	Shunt Susceptance = 1.14015e-3 p.u./km
I_{p3}	0.4485 + j0.4331	
V_{q3}	0.9515 – j0.08263	
I_{q3}	-0.5714 – j0.03201	
V_{p4}	0.8709 + j0.4630	Unsynchronization Angle=20 degrees
I_{p4}	0.4748 + j0.4917	
V_{q4}	0.8739 – j0.3907	
I_{q4}	-0.6110 + j0.1392	

Table 3.3 represents the estimation results with four sets of measurements, with an unsynchronization angle of 40 degrees.

Table 3-3: Estimation results using four sets of measurements with an unsynchronization angle of 40 degrees

Quantities	**Measured values (p.u.)**	**Estimated Parameters**
V_{p1}	0.9325 + j0.3214	
I_{p1}	0.4110 + j0.3636	Series Resistance =
V_{q1}	0.8329 – j0.4895	6.19303e-4 p.u./km
I_{q1}	-0.4515 + j0.1865	
V_{p2}	0.9010 + j0.4012	
I_{p2}	0.4379 + j0.4083	Series Reactance =
V_{q2}	0.8570 – j0.4268	1.46432e-3 p.u./km
I_{q2}	-0.5173 + j0.1755	
V_{p3}	0.8865 + j0.4324	
I_{p3}	0.4485 + j0.4331	Shunt Susceptance = 1.14015e-3 p.u./km
V_{q3}	0.8659 – j0.4030	
I_{q3}	-0.5478 + j0.1653	
V_{p4}	0.8709 + j0.4630	
I_{p4}	0.4748 + j0.4917	Unsynchronization Angle = 40 degrees
V_{q4}	0.8739 – j0.3907	
I_{q4}	-0.6110 + j0.1392	

Tables 1, 2 and 3 reveal that the proposed approach is able to accurately estimate the positive sequence of long line parameters using unsynchronized data.

Tables 4 and 5 examine the impact of possible voltage errors on estimation results. To perform the study, errors are applied to one set of voltage measurements at terminal q. Table 4 shows results with 1% voltage error, and Table 5 shows results with 2% voltage error.

Table 3-4 : Estimation results with 1% error in voltage measurements at terminal q

Quantities	**Measured values (p.u.)**	**Estimated Parameters**
V_{p1}	0.9325 + j0.3214	
I_{p1}	0.4110 + j0.3636	Series Resistance =
V_{q1}	0.9502 – j0.1751	6.82672e-04 p.u./km
I_{q1}	-0.4881 + j0.02081	
V_{p2}	0.9010 + j0.4052	Series Reactance =
I_{p2}	0.4379 + j0.4083	1.38876e-3 p.u./km
V_{q2}	0.9608 – j0.1090	
I_{q2}	-0.5461 – j0.01210	Shunt Susceptance = 1.1324e-3 p.u./km
V_{p3}	0.8865 + j0.4324	
I_{p3}	0.4485 + j0.4331	Unsynchronization
V_{q3}	0.9515 – j0.0826	Angle= 20.38 degrees
I_{q3}	-0.5714 – j0.03201	

The results presented in Table 4 and 5 indicate that the proposed method still produces reliable estimates when voltage measurements contain possible measurement errors. Similarly, the impact of possible errors contained in current measurements is also examined. Table 6 shows the estimated line parameters using three sets of data, with 1% error added to the I_{p3} at terminal p.

Table 3-5: Estimation results with adding 2% error to the voltage at terminal q

Quantities	Measured values (p.u.)	Estimated Parameters
V_{p1}	0.9325 + j0.3214	Series Resistance = 7.15169e-04 p.u./km
I_{p1}	0.4110 + j0.3636	
V_{q1}	0.9502 – j0.1751	
I_{q1}	-0.4881 + j0.02081	Series Reactance = 1.12739e-3 p.u./km
V_{p2}	0.9010 + j0.4052	
I_{p2}	0.4379 + j0.4083	
V_{q2}	0.9703 – j0.1101	Shunt Susceptance = 1.09211e-3 p.u./km
I_{q2}	-0.5461 – j0.01210	
V_{p3}	0.8865 + j0.4324	
I_{p3}	0.4485 + j0.4331	Unsynchronization Angle= 21.94 degrees
V_{q3}	0.9515 – j0.0826	
I_{q3}	-0.5714 – j0.03201	

Table 3-6: Estimation results with added 1% error to the current at terminal *P*

Quantities	Measured values (p.u.)	Estimated Parameters
V_{p1}	0.9325 + j0.3214	Series Resistance = 6.45701e-04 p.u./km
I_{p1}	0.4110 + j0.3636	
V_{q1}	0.9502 – j0.1751	
I_{q1}	-0.4881 + j0.02081	Series Reactance = 1.41803e-3 p.u./km
V_{p2}	0.9010 + j0.4012	
I_{p2}	0.4379 + j0.4083	
V_{q2}	0.95134 – j0.1079	Shunt Susceptance = 1.13743e-3 p.u./km
I_{q2}	-0.5461 – j0.01210	
V_{p3}	0.8865 + j0.4324	
I_{p3}	0.4529 + j0.4374	Unsynchronization Angle= 20.23 degrees
V_{q3}	0.9515 – j0.0826	
I_{q3}	-0.5714 – j0.03201	

Table 7 shows estimation results with three sets of data, with 2% error added to I_{p3} at terminal P. The error can be implemented to any set of measurements, and it will yield similar results.

Table 3-7: Estimation of line parameters with adding 2% error to the current at terminal *P*

Quantities	Measured values (p.u.)	Estimated Parameters
V_{p1}	0.9325 + j0.3214	
I_{p1}	0.4110 + j0.3636	Series Resistance =
V_{q1}	0.9502 – j0.1751	6.68682e-04 p.u./km
I_{q1}	-0.4881 + j0.02081	
V_{p2}	0.9010 + j0.4012	Series Reactance =
I_{p2}	0.4379 + j0.4083	1.37322e-3 p.u./km
V_{q2}	0.95134 – j0.1079	
I_{q2}	-0.5461 – j0.01210	Shunt Susceptance =
V_{p3}	0.8865 + j0.4324	1.13428e-3 p.u./km
I_{p3}	0.4574 + j0.4417	
V_{q3}	0.9515 – j0.0826	Unsynchronization
I_{q3}	-0.5714 – j0.03201	Angle= 20.46 degrees

The results displayed in Tables 6 and 7 indicate that the proposed algorithm still produces reliable results when current measurements contain measurement errors. It can also be seen that the method is more sensitive to voltage measurement errors than to current measurement errors.

3.4.2 Case 2 (Double Circuits Transmission Line)

This section illustrates results using the second transmission model. The Matlab simulation and modeling were used to generate the currents and voltages, and the three-phase sources were connected to each end of the transmission line. Several sets of measurements were taken by varying the internal phase angle difference of the connected sources to the system. All results shown in the next tables are in per unit; also, the currents and voltages are in per unit. 350 and 300 km are the line lengths for both lines 1 and 2 respectively. The two transmission lines are assumed to be transposed and have different values for the series impedances as well as the shunt susceptance. The exact transmission line parameters are:

- **Line 1**
  - Series Resistance

$$R = 6.19303 \times 10^{-4}\ \mathrm{p.u./km}$$

  - Series inductance

$$L = 1.46432 \times 10^{-3}\ \mathrm{p.u./km}$$

  - Shunt Capacitance

$$C = 1.14016 \times 10^{-3}\ \mathrm{p.u./km}$$

- **Line 2**
  - Series Resistance

$$R = 8.099303 \times 10^{-4}\ \mathrm{p.u./km}$$

  - Series inductance

$$L = 1.312879 \times 10^{-3}\ \mathrm{p.u./km}$$

  - Shunt Capacitance

$$C = 1.234400 \times 10^{-3}\ \mathrm{p.u./km}$$

Table 3-8: Estimation results with four sets of measurements

Quantities	First Set	Second Set	Third Set	Fourth Set
V_{p1}	1.08942 + 0.09720i	1.03370+ 0.27628i	0.98116+ 0.41939i	0.88650+ 0.57643i
I_{p1}	0.25606 + 0.50870i	0.13830+ 0.57875i	0.21813+ 0.66697i	0.08670+ 0.70694i
V_{p2}	1.06094 - 0.15790i	1.08940+ 0.02691i	1.08331+ 0.17568i	1.03381+ 0.35928i
I_{p2}	-0.21687 +0.35236i	-0.25569 +0.28463i	-0.10987 +0.33726i	-0.170288 +032371i
V_{p3}	1.17791- 0.09651i	1.17877+ 0.10677i	1.15360+0 .17564i	1.10821+ 0.37048i
Line 1 Parameters	R= 0.0006151 8 p.u /km	L= 0.00146 836 p.u/km	C= 0.001143449 p.u/km	
Errors	0.66%	0.27%	0.28%	
Line 2 Parameters	R= 0.0008050 0 p.u/km	L= 0.00131717 p.u/km	C= 0.0012344739 p.u/km	
Errors	0.60%	0.32%	0.00%	

The next step is to validate the results for the possible errors that the measurement may contain. An error of 2% is added to the voltages and currents. The four sets of measurements are used to evaluate the impact of these errors. The errors will be added randomly to the sets.

Table 3-9: Estimated parameters with 2% error on the voltage at P_2 end

Quantities	First Set	Second Set	Third Set	Fourth Set
V_{p1}	1.08942 + 0.09720i	1.03370+ 0.27628i	0.98116+ 0.41939i	0.88650+ 0.57643i
I_{p1}	0.25606 + 0.50870i	0.13830+ 0.57875i	0.21813+ 0.66697i	0.08670+ 0.70694i
V_{p2}	1.06094 - 0.15790i	1.08940+ 0.02691i	1.08331+ 0.17568i	1.03381+ 0.35928i
I_{p2}	-0.21687 +0.35236i	-0.25569 +0.28463i	-0.10987+ 0.33726i	-0.17028 + 032371i
V_{p3}	1.17791- 0.09651i	1.17877+ 0.10677i	1.15360+ 0.17564i	1.10821+ 0.37048i
Line 1 Parameters	R = 0.0007636 p.u /km	L = 0.00135473 p.u/km		C = 0.00087101 p.u/km
Errors	23.30%	7.48%		23.60%
Line 2 Parameters	R = 0.00102361 p.u/km	L = 0.00134955 p.u/km		C = 0.00133965 p.u/km
Errors	26.38%	2.79%		8.52%

Table 3-10: Estimation results using four sets of measurements with 2% error on the third set p_1 voltage

Quantities	First Set	Second Set	Third Set	Fourth Set
V_{p1}	1.08942+ 0.09720i	1.03370+ 0.27628i	1.000784+ 0.42778i	0.88650+ 0.57643i
I_{p1}	0.25606 + 0.50870i	0.13830+ 0.57875i	0.21813+ 0.66697i	0.08670+ 0.70694i
V_{p2}	1.06094 - 0.15790i	1.08940+ 0.02691i	1.08331+ 0.17568i	1.03381+ 0.35928i
I_{p2}	-0.21687 +0.35236i	-0.25569 +0.28463i	-.10987 +0.33726i	-0.17028+ 032371i
V_{p3}	1.17791- 0.09651i	1.17877+ 0.10677i	1.15360+ 0.17564i	1.10821+ 0.37048i
Line 1 Parameters	R = 0.00076497 p.u /km	L = 0.00135624 p.u/km	C = 0.000965617 p.u/km	
Errors	23.52%	7.37%	15.30%	
Line 2 Parameters	R = 0.00080500 p.u /km	L = 0.00131717 p.u /km	C = 0.00123447 p.u/km	
Error	0.60%	0.32%	6.01%	

Table 3-11: Estimation results using four sets of measurements with 2% error on the second set p_2 voltage

Quantities	First Set	Second Set	Third Set	Fourth Set
V_{p1}	1.08942 + 0.09720i	1.03370+ 0.27628i	0.98116+ 0.41939i	0.88650+ 0.57643i
I_{p1}	0.25606 + 0.50870i	0.13830+ 0.57875i	0.21813+ 0.66697i	0.08670+ 0.70694i
V_{p2}	1.06094 - 0.15790i	1.11119+ 0.027453i	1.08331+ 0.17568i	1.03381+ 0.35928i
I_{p2}	-0.21687 +0.35236i	-0.25569 +0.28463i	-0.10987+ 0.33726i	-0.170288+ 032371i
V_{p3}	1.17791- 0.09651i	1.17877+ 0.10677i	1.15360+ 0.17564i	1.10821+ 0.37048i
Line 1 Parameters	Series Resistance 0.000615182 p.u /km	Series Reactance 0.00146836p.u/km	Shunt Susceptance 0.00114384 p.u/km	
Line 2 Parameters	Series Resistance 0.00061371p.u/km	Series Reactance 0.00128715 p.u/km	Shunt Susceptance 0.00113348p.u/km	

Tables 3.9, 3.10 and 3.11 illustrate the cases with possible errors on the receiving end of p_3 and the two sending ends p_1 and p_2 respectively, with 2% error being added to one set of voltage measurements each time. Results show that estimation results are still quite accurate with the added measurement errors.

Tables 11 and 12 exhibit the estimated parameters with 2% error added to the one set of p_1 and p_2 currents.

Table 3-12: Estimation results using four sets of measurements with 2% error on the second set p_1 current

Quantities	First Set	Second Set	Third Set	Fourth Set
V_{p1}	1.08942 + 0.09720i	1.03370+ 0.27628i	0.98116+ 0.41939i	0.88650+ 0.57643i
I_{p1}	0.25606 + 0.50870i	0. 14107+ 0.59033i	0.21813+ 0.66697i	0.08670+0.70694i
V_{p2}	1.06094 - 0.15790i	1.08940+ 0.02691i	1.08331+ 0.17568i	1.03381+ 0.35928i
I_{p2}	-0.21687 +0.35236i	-0.25569 +0.28463i	-.10987 + 0.33726i	-0.17028 +032371i
V_{p3}	1.17791- 0.09651i	1.17877+ 0.10677i	1.15360+ 0.17564i	1.10821+ 0.37048i
Line 1 Parameters	R = 0.00060680 p.u /km	L = 0.00151808 p.u/km	C = 0.00122822 p.u/km	
Errors	2.01%	3.67%	7.72%	
Line 2 Parameters	R = 0.00080500 p.u/km	L = 0.00131717 p.u/km	C = 0.0012344739 p.u/km	
Errors	0.60%	0.32%	0.00%	

Table 3-13: Estimation results using four sets of measurements with 2% error on the first set p_2 current

Quantities	First Set	Second Set	Third Set	Fourth Set
V_{p1}	1.08942 + 0.09720i	1.03370+ 0.27628i	0.98116+ 0.41939i	0.88650+ 0.57643i
I_{p1}	0.25606 + 0.50870i	0. 14107+ 0.59033i	0.21813+ 0.66697i	0.08670+ 0.70694i
V_{p2}	1.06094 - 0.15790i	1.08940+ 0.02691i	1.08331+ 0.17568i	1.03381+ 0.35928i
I_{p2}	-0.221209 + 0.35941i	-0.25569 + 0.28463i	-.10987 + 0.33726i	-0.17028 +032371i
V_{p3}	1.17791- 0.09651i	1.17877+ 0.10677i	1.15360+ 0.17564i	1.10821+ 0.37048i
Line 1 Parameters	R = 0.00061518 p.u /km	L = 0.00146836 p.u/km	C = 0.00114384 p.u/km	
Errors	0.66%	0.27%	0.32%	
Line 2 Parameters	R = 0.00077201 p.u/km	L = 0.00133219 p.u/km	C = 0. 00122240 p.u/km	
Errors	4.68%	1.47%	0.97%	

Table 3-14 Estimation of long Transmission line parameters using synchronized data

Quantities	Measured values (p.u.)	Estimated Parameters
V_{p1}	0.9449811+ 0.33823i	Series Resistance = 6.19303e-4 p.u./km Series Reactance = 1.46432e-3 p.u./km Shunt Susceptance = 1.14015e-3 p.u./km Unsynchronization Angle = 0 degrees
I_{p1}	0.21328 + 0.3349780i	
V_{q1}	0.98022 + 0.237721i	
I_{q1}	0.278791 - 0.114088i	
V_{p2}	0.9248901+ 0.3904323i	
I_{p2}	0.32610 + 0.386654i	
V_{q2}	0.96140 + 0.248909i	
I_{q2}	-0.3988902 - 0.170208i	
V_{p3}	0.900220+ 0.403453i	
I_{p3}	0.3719982+ 0.391107i	
V_{q3}	0.933104 + 0.247294i	
I_{q3}	-0.44611 - 0.180732i	

3.4.3 Case 3 study of the second case

The Matlab simulation and SimPower tool are used to represent the transmission line that is mentioned in figure 3-2. The four sets of measurements are obtained by changing the internal phase shift of the three sources. The base voltage is 500 kV, and the base power $1000MVA$. Both line lengths for 1 and 2 are 350km and 300 km respectively. These two transmission lines are assumed to be transposed and each line has a different value for the series impedances as well as the shunt susceptance. The exact transmission line parameters are the same as that used in section 3.4.2.

Table 3-15 shows the four sets of measurements that are used to estimate the positive sequence of the long transmission line.

Table 3-15 Estimation results using the third method for long line

V_{p1}	I_{p1}	V_{p2}	I_{p2}
1.0894 + 0.0972i	0.2561 + 0.5087i	1.0609 - 0.1579i	-0.2169 + 0.3524i
1.0337 + 0.2763i	0.1383 + 0.5788i	1.0894 + 0.0269i	-0.2557 + 0.2846i
0.9812 + 0.4194i	0.2181 + 0.6670i	1.0833 + 0.1757i	-0.1099 + 0.3373i
0.8865 + 0.5764i	0.0867 + 0.7069i	1.0338 + 0.3593i	-0.1703 + 0.3237i

Since the known quantities are reduced, and the unknown variables are remaining the same, by using the developed method, the results cannot be determined due to an ill-conditioned matrix.

3.5 Conclusion

This chapter presents an online algorithm that linearly estimates the positive-sequence parameters of long transmission lines. The proposed approach utilizes two terminals unsynchronized measurements including voltages and currents that are taken at different times. The proposed method is based on a distributed parameter long line model, so the shunt capacitances are accurately modeled.

Two models are utilized in this chapter. The first model is a long transmission line implementing unsynchronized data, and this method requires implementation of the voltages and currents at both ends. Case studies show that the proposed method produces more reliable and accurate results, and the errors have been added to one set of measurements each time to test the robustness of the linear method.

The second model is the long transmission line with three nodes. This model implements synchronized data and requires less data than the first model. All data that are needed are the voltages at all nodes and currents at the two sending end nodes; the errors have been added to examine the proposed algorithm.

The proposed algorithm should be applicable to both single and double circuit long transmission lines, and the developed algorithm requires at least two sets of measurements to estimate the line parameters correctly. The case studies indicate that the proposed method has achieved accurate results. The linear method is technically sound and more computationally efficient than existing nonlinear methods.

Chapter 4

Medium Transmission Line

4.1 Introduction

Medium transmission lines are widely used to transmit electricity from one end to another. The length of a medium transmission line between 80 and 250 km. The medium transmission line is usually used for a voltage level between 30 kV to 250 kV.

This chapter only considers the positive sequence of line parameters to be estimated. The two different medium-length transmission line configurations are modeled to estimate the line parameters. The linear least square method and the four sets of measurements are used to estimate a positive sequence of the line parameters. The developed method is capable of handling synchronized and unsynchronized data and is also able to consider possible errors due to receiving PMU readings or the inaccuracy of PMU measurements themselves.

Medium Lines are usually modeled with pure shunt capacitance, and to get a more accurate estimation of the line parameters, the shunt capacitance must be considered in the calculation. There are two different medium transmission line configurations:

- Nominal PI circuit: In this configuration, the lumped series impedance is placed between two shunt capacitances; the shunt capacitances have the same values, and they have half the value of the total capacitance.

- Nominal T circuit: In this circuit, the total lumped admittance is placed at the middle of the circuit, and the lumped series impedance is divided into equal parts, each part placed on each end.

The medium transmission line is operated under sinusoidal, steady-state and balanced three-phase. The transmission line is assumed to be transposed along the line.

The remainder of this chapter is organized as follows: section 4.2 presents the proposed approach based on the single circuit nominal PI of the medium transmission line. The derivation of the proposed method with double circuit transmission line is used as presented in section 4.3. Section 4.4 illustrates the results with discussion for both case studies, the conclusion presented in section 4.5.

4.2 Proposed Method for Single Circuit Medium Transmission Line

The medium transmission line usually considers the shunt capacitance in the calculation. A medium transmission line is the transmission line whose length is between 80 km and 250 km. Because of the relatively long length, the shunt branch of the circuit can play an important role in calculating circuit parameters, unlike in the case of short transmission lines. As a result, the medium length transmission line is modeled using lumped shunt admittance along with lumped impedance in series. These lumped parameters of medium length transmission lines can be represented using two different models such as nominal PI representation or nominal T representation. If the total shunt admittance of the line is divided into two equal parts placed at two end ends while the total circuit impedance is between the shunt branches, the circuit is called nominal PI as shown in Figure 4-1.

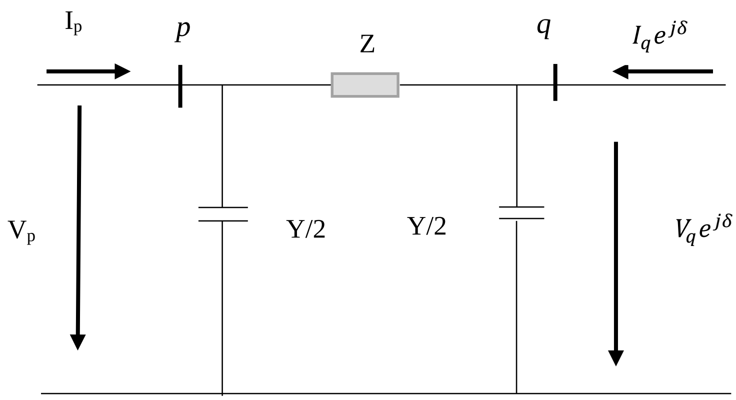

Figure 4-1 Nominal PI Circuit of Positive Sequence Single-Circuit Transmission Line

The following notations are used in this chapter:

V_p , V_q : The positive sequence voltage phasors at two terminals p and q;

I_p and I_q: The positive sequence current phasors at two terminals p and q;

Z: The positive-sequence series impedance per unit of length;

Y: The positive-sequence shunt susceptance per unit of length;

δ : The unsynchronization angle;

l : The line length.

It follows from Figure 4-1 that

$$I_p = \left(1/Z + \frac{Y}{2}\right) V_p - (1/Z)\ V_q\ e^{j\delta} \tag{4.1}$$

$$I_q e^{j\delta} = (Y/2 + (1/Z))\ V_q\ e^{j\delta} - (1/Z) V_p \tag{4.2}$$

where Z is the lumped series impedance

$$Z = R + j\ wL \tag{4.3}$$

Defining the unknown parameters in (4-1) and (4-2) as

$$A = (1/Z + Y/2)$$

Equations (4.1) and (4.2) can be rewritten regarding to the new variables as

$$I_p = A\,V_p - (1/Z)\;V_q\,e^{j\delta} \tag{4.4}$$

$$I_q e^{j\delta} = A\;V_q\,e^{j\delta} - (1/Z)\,V_p \tag{4.5}$$

Since the unknown variables are [A, δ], equations (4.4) and (4.5) will be written as linear equations

$$I_p = A\,V_p - (1/Z)e^{j\delta}\;\;V_q \tag{4.6}$$

$$I_q = A\;V_q - (1/Z)\,e^{-j\delta}\,V_p \tag{4.7}$$

Introducing new variables B and C which are

$$B = (-1/Z)\,e^{j\delta}$$

$$C = (-1/Z)\,e^{-j\delta}$$

The unsynchronization angle is denoted as δ, which will have zero value when synchronous measurements are applied. Introducing this angle makes it possible to detect synchronization errors even with synchrophasors. Therefore, the following equation can be obtained

$$\begin{bmatrix} I_p \\ I_q \end{bmatrix} = \begin{bmatrix} V_p & V_q & 0 \\ V_q & 0 & V_p \end{bmatrix} \begin{bmatrix} A \\ B \\ C \end{bmatrix} \tag{4.8}$$

Since there are three unknown variables, two sets of measurements are required, equation (4.8) can be expanded into

$$\begin{bmatrix} I_{p1} \\ I_{q1} \\ I_{p2} \\ I_{q2} \end{bmatrix} = \begin{bmatrix} V_{p1} & V_{q1} & 0 \\ V_{q1} & 0 & V_{p1} \\ V_{p2} & V_{q2} & 0 \\ V_{q2} & 0 & V_{p2} \end{bmatrix} \begin{bmatrix} A \\ B \\ C \end{bmatrix} \tag{4.9}$$

Equation (4.9) can be solved using the linear least square method

$$U = H\,X \tag{4.10}$$

Where H is the two terminal p_1 and p_2 node voltages, U the two line currents, and X is the unknown variable. The solution for equation (4.10)

$$X = (H^T\,H)^{-1}\;(H^T\,U) \tag{4.11}$$

By using the relations

$$A = (1/Z + Y/2)$$

$$B = (-1/Z)\,e^{j\delta}$$

$$C = (-1/Z)\,e^{-j\delta}$$

From B and C, it is easy to calculate the line impedance and unsynchronization angle. Then the line impedance can be obtained as

$$Z = \sqrt{1/BC} \tag{4.12}$$

The shunt admittance can be calculated using the first two notations A and B.

$$Y/2 = A + (1/Z) \tag{4.13}$$

Once Z and Y are estimated, the series resistance, reactance and shunt susceptance per km or per mile can be obtained by dividing Z and Y by the length of the line for medium-length line. For long lines, the line parameters per km can be obtained by solving hyperbolic equations as shown in chapter 3.

4.3 Double circuit medium-length transmission Line

Figure 4-2 represents the medium transmission line with three nodes, the two nodes on the left hand being the sending end, and the node on the right hand being the receiving end. This module is used to estimate the medium line parameters using the voltages and currents at nodes p_1 and p_2 and the voltage at node p_3. The *Z1* and *Z2* are the total series impedances for line 1 and 2 respectively. *Y1* and *Y2* are the total shunt admittance of the lines.

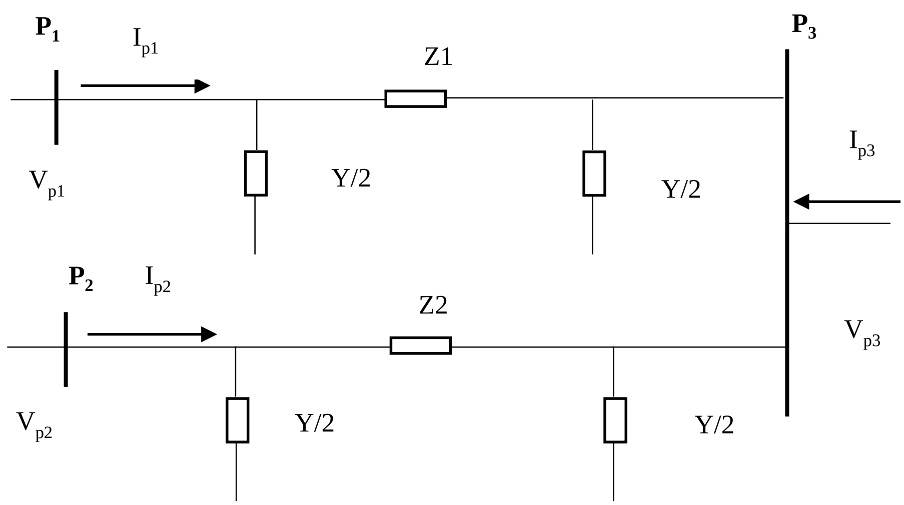

Figure 4-2 Nominal PI Circuit of Positive Sequence for Double-Circuit Medium Transmission Line

Referring to the figure 4-2 above, with synchronous phasor data adopted, for the line segment p_1 to p_3, we obtain

$$V_{p3} = V_{p1} - \left(I_{p1} - V_{p1}\frac{Y1}{2}\right)Z1 \qquad (4.14)$$

Likewise, for the line segment p_2 to p_3, we obtain

$$V_{p3} = V_{p2} - \left(I_{p2} - V_{p2}\frac{Y2}{2}\right)Z2 \qquad (4.15)$$

Since the known variables are $[V_{p3}, V_{p2}, V_{p1}, I_{p1}, I_{p2}]$, and the unknown parameters are $[\mathrm{Z}1, Y1, Z2, Y2]$, equations (4.14) and (4.15) can be rewritten in terms of the four unknown variable as follows:

$$V_{p3} = V_{p1}\left(1 + Z1\,\frac{Y1}{2}\right) - I_{p1}Z1 \tag{4.16}$$

$$V_{p3} = V_{p2}\left(1 + Z2\,\frac{Y2}{2}\right) - I_{p2}Z2 \tag{4.17}$$

By augmenting equations (4.16) and (4.17), we get

$$\begin{bmatrix} V_{p3} \\ V_{p3} \end{bmatrix} = \begin{bmatrix} V_{p1}\left(1 + Z1\,\frac{Y1}{2}\right) - I_{p1}Z1 \\ V_{p2}\left(1 + Z2\,\frac{Y2}{2}\right) - I_{p2}Z2 \end{bmatrix} \tag{4.18}$$

Equation (4.18) can be modified as

$$\begin{bmatrix} V_{p3} \\ V_{p3} \end{bmatrix} = \begin{bmatrix} V_{p1} & -I_{p1} & 0 & 0 \\ 0 & 0 & V_{p2} & -I_{p2} \end{bmatrix} \begin{bmatrix} \left(1 + Z1\,\frac{Y1}{2}\right) \\ Z1 \\ \left(1 + Z2\,\frac{Y2}{2}\right) \\ Z2 \end{bmatrix} \tag{4.19}$$

Equation (4.19) can be expanded for any number of measurements. Equation (4.19) can be solved using the linear least square method as

$$U = H\,X \tag{4.20}$$

where H is the two nodes' p_1 and p_2 voltages and currents, U is the voltage at node p_3, and X is a set of unknown variables which can be expressed as

$$X = \begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix} \tag{4.21}$$

where these variables are defined as;

$$A = \left(1 + Z1\ \frac{Y1}{2}\right)$$

$$B = Z1$$

$$C = \left(1 + Z2\ \frac{Y2}{2}\right)$$

$$D = Z2$$

The solution for equation (4.20)

$$X = (H^T\ H)^{-1}\ (H^T\ U) \tag{4.22}$$

B and *D* relations can directly determine the series impedances for both lines. The shunt element can be calculated by using

$$\frac{Y}{2} = (A - 1)/Z1 \tag{4.23}$$

The line parameters per km can be obtained similarly to single-circuit lines.

4.4 Results and Discussion

In this chapter, I utilize Matlab simulation and modeling. This modeling is used to generate the data by applying either multiple loads or changing the phase angle to obtain multiple sets of measurements. The two transmission lines are assumed to be medium lines with different line parameters. These lines are assumed to operate under normal conditions and steady state.

All data shown in tables are measured in per unit with a base of 500 kV and 1000 MVA. The developed algorithm has been implemented in Matlab.

4.4.1 Case 1: Medium Transmission Line single line circuit

The SimPowerSystem tool in Matlab is utilized to generate all data such as voltages and currents at both ends. The two PMU as shown in figure 4.3 are installed at both ends to get the data. These data are stamped with the precise time.

Multiple sets of measurements are generated using figure 4-3 by either varying the internal phase shift difference or by applying multiple different loads.

This chapter adapts the per unit system with 500 kV base voltage and 1000 MVA as base power. All results that shown in next tables for both case studies are in per unit, and line parameters are in per unit of length.

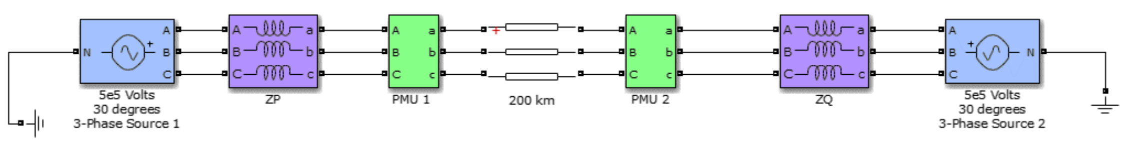

Figure 4-3 Medium transmission line

The exact transmission line parameters are shown below. The developed algorithm is capable of estimating the line parameters using either synchronized or unsynchronized data.

- Series Resistance

$$R = 6.19303 \times 10^{-4} \text{ p.u./km}$$

- Series Inductance

$$L = 1.46432 \times 10^{-3} \text{ p.u./km}$$

- Shunt Capacitance

$$C = 1.14016 \times 10^{-3} \text{ p.u./km}$$

Table 4-1 shows the estimation of the positive sequence parameters of the medium transmission line using four sets of measurements and unsynchronized data.

Table 4-1: Estimation results with four sets of measurements

Quantities	Measured values	Estimated Parameters
V_{p1}	1.02508 + 0.12220i	Series Resistance = 6.19303e-4 p.u./km
I_{p1}	-0.25984 - 0.08413i	
V_{q1}	1.01958 + 0.04271i	
I_{q1}	0.27221 + 0.27150i	
V_{p2}	0.97234+ 0.29270i	Series Reactance = 1.46435e-3 p.u./km
I_{p2}	-0.25976- 0.10241i	
V_{q2}	0.99060 + 0.21669i	
I_{q2}	0.23527 + 0.28366i	Shunt Susceptance = 1.14015e-3 p.u./km
V_{p3}	0.92265 + 0.43810i	
I_{p3}	-0.15144 - 0.05423i	
V_{q3}	0.95969 + 0.32587i	Unsynchronization Angle = 9.99998 degrees
I_{q3}	0.09048 + 0.24880i	
V_{p4}	0.81713+ 0.60977i	
I_{p4}	-0.22405 - 0.17884i	
V_{q4}	0.86471 + 0.54687i	
I_{q4}	0.13706 + 0.33963i	

The next two tables, 4-2 and 4-3, show the negative impact of adding some errors on one set of measurements of the current or voltage. Table 4-2 shows that the voltage at node *P* has 2% error on the second measurement. The developed algorithm can still estimate the line parameters accurately. The robustness of the algorithm is tested when the current I_{q1}

has errors as shown in Table 4-3, and the results show that the algorithm is still effective in estimating the accurate line parameters.

Table 4-2 Estimated line parameters with 2% error added to V_{p2}

Quantities	Measured values	Estimated Parameters
V_{p1}	1.02508 + 0.12220i	Series Resistance = 6.48884e-4 p.u./km
I_{p1}	-0.25984 - 0.08413i	
V_{q1}	1.01958 + 0.04271i	
I_{q1}	0.27221 + 0.27150i	Series Reactance = 1.20933e-3 p.u./km
V_{p2}	1.01041 + 0.22103i	
I_{p2}	-0.25976- 0.10241i	
V_{q2}	0.99060 + 0.21669i	Shunt Susceptance = 1.215633e-3 p.u./km
I_{q2}	0.23527 + 0.28366i	
V_{p3}	0.92265 + 0.43810i	Unsynchronization Angle = 9.31684 degrees
I_{p3}	-0.15144 - 0.05423i	
V_{q3}	0.95969 + 0.32587i	
I_{q3}	0.09048 + 0.24880i	
V_{p4}	0.81713+ 0.60977i	
I_{p4}	-0.22405 - 0.17884i	
V_{q4}	0.86471 + 0.54687i	
I_{q4}	0.13706 + 0.33963i	

Table 4-3 Estimation results using four sets of measurements with 2% error added to I_{q1}

Quantities	Measured values	Estimated Parameters
V_{p1}	1.02508 + 0.12220i	
I_{p1}	-0.25984 - 0.08413i	Series Resistance = 6.24214e-4 p.u./km
V_{q1}	1.01958 + 0.04271i	
I_{q1}	0.27765 + 0.27693i	
V_{p2}	0.97234+ 0.29270i	Series Reactance = 1. 44522e-3 p.u./km
I_{p2}	-0.25976- 0.10241i	
V_{q2}	0.99060 + 0.21669i	
I_{q2}	0.23527 + 0.28366i	Shunt Susceptance = 1.14287e-3 p.u./km
V_{p3}	0.92265 + 0.43810i	
I_{p3}	-0.15144 - 0.05423i	
V_{q3}	0.95969 + 0.32587i	Unsynchronization Angle = 9.96933 degrees
I_{q3}	0.09048 + 0.24880i	
V_{p4}	0.81713+ 0.60977i	
I_{p4}	-0.22405 - 0.17884i	
V_{q4}	0.86471 + 0.54687i	
I_{q4}	0.13706 + 0.33963i	

4.4.2 Case 2 Double Circuit Medium Transmission Line

The two transmission lines are assumed to be medium lines with different line parameters. These lines are assumed to be operated under normal conditions and steady state. The lengths of the two lines are 200 km and 130 km for lines 1 and 2, respectively. Figure 4.4 shows the Matlab simulation model that used to generate the data

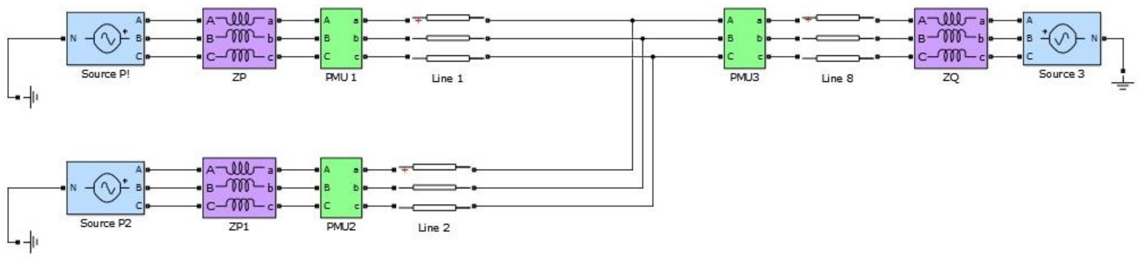

Figure 4-4 Medium transmission line Matlab representation

The actual line parameters are:

- Transmission Line 1

  Series resistance = 0.0006193032 p.u./km

  Series reactance = 0.001464328 p.u./km

  Shunt susceptance = 0.001140153 p.u./km

- Transmission Line 2

  Series resistance = 0.0008099303 p.u./km

  Series reactance = 0.001312879 p.u./km

  Shunt susceptance = 0.001234400 p.u./km

Table 4-4 shows the estimated line parameters using the proposed method. It is evinced that highly accurate results have been achieved.

Table 4-4 Estimated line parameters for double-circuit medium transmission lines

Quantities	First Set	Second Set	Third Set	Fourth Set
V_{p1}	1.02638 + 0.10265i	0.98766 + 0.26435i	0.92731 + 0.43242i	0.83980 + 0.58806i
I_{p1}	0.27906 + 0.30643i	0.27624 + 0.38308i	0.20965 + 0.42042i	0.13370 + 0.45140i
V_{p2}	1.02978 - 0.00360i	1.01482 + 0.15801i	0.97077 + 0.33161i	0.90025+ 0.49613i
I_{p2}	-0.03849 + 0.15453i	0.01531+ 0.18140i	-0.01658 + 0.17996i	-0.04776 +0.17482i
V_{p3}	1.04606 - 0.00446i	1.02887 + 0.14285i	0.98711 + 0.31931i	0.91849 + 0.48683i

Estimated Transmission Line Parameters			
Line 1	R = 0.000609210 p.u. /km	L= 0.001449877 p.u./km	C = 0.00113740 p.u./km
Errors	1.65%	0.99%	0.24%
Line 2	R= 0.0008020238 p.u./km	L= 0.001308731 p.u./km	C= 0.00123635 p.u./km
Errors	0.38%	0.31%	0.15%

To examine the effectiveness of the proposed method of estimating parameters lines that longer than medium-length lines, the proper method is applied to long lines. Table 4-5 shows the evaluation of the long transmission line, where the length of the two lines are

280km and 200 km respectively. The results indicate that the algorithm provides accurate results for long lines as well.

Table 4-5 Estimated line parameters for long lines

Quantities	**First Set**	**Second Set**	**Third Set**	**Fourth Set**
V_{p1}	1.03605 + 0.119205i	0.997459+ 0.296553i	0.928298+ 0.47481i	0.838318 + 0.621859i
I_{p1}	0.17132+ 0.34061i	0.10699+ 0.36794i	0.00804 + 0.34511i	-0.02140 + 0.38047i
V_{p2}	1.04172 + 0.00234i	1.02619+ 0.18322i	0.95659+ 0.42097i	0.90223+ 0.52360i
I_{p2}	-0.08892+ 0.20113i	-0.12055+ 0.18039i	-0.07975+ 0.24125i	-0.17525+ 0.12807i
V_{p3}	1.07461+ 0.01428i	1.05533+ 0.20050i	0.99296+ 0.40896i	0.92389+ 0.55005i

Estimated Transmission Line Parameters			
Line1	R =0.00059043 p.u. /km	L = 0.00143877 p.u./km	C = 0.0011523 p.u./km
Errors	4.89%	1.77%	1.05%
Line 2	R = 0.0007879 p.u./km	L = 0.00130658 p.u./km	C = 0.0012412 p.u./km
Errors	2.18%	0. 48%	0.54%

Table 4-6 shows the results for estimating the line parameters using the method that has been derived in section 3.4. The method in 3.4 is for estimating line positive sequence parameters of the long transmission line. The results indicate that the developed method still produces accurate results for the medium transmission line.

Table 4-6 Estimated line parameters for overlength lines

Quantities	First Set	Second Set	Third Set	Fourth Set
V_{p1}	1.03605 + 0.119205i	0.997459+ 0.296553i	0.928298+ 0.47481i	0.838318 + 0.621859i
I_{p1}	0.17132+ 0.34061i	0.10699+ 0.36794i	0.00804 + 0.34511i	-0.02140 + 0.38047i
V_{p2}	1.04172 + 0.00234i	1.02619+ 0.18322i	0.95659+ 0.42097i	0.90223+ 0.52360i
I_{p2}	-0.08892+ 0.20113i	-0.12055+ 0.18039i	-0.07975+ 0.24125i	-0.17525+ 0.12807i
V_{p3}	1.07461+ 0.01428i	1.05533+ 0.20050i	0.99296+ 0.40896i	0.92389+ 0.55005i
Estimated Transmission Line Parameters				
Line1	R =6.171875e-4 p.u. /km	L = 0.0014648 p.u./km	C = 0.0011397 p.u./km	
Errors	0.3427%	0.03845%	0.03273%	
Line 2	R = 0.00080526 p.u./km	L = 0.0013155 p.u./km	C = 0.00123449 p.u./km	
Errors	0.02%	44.70%	0.00%	

4.5 Conclusion

This chapter presents a linear estimation method to estimate the positive sequence line parameters for medium-length lines. For this purpose, different transmission line configurations are used to examine and assess the effectiveness of the developed algorithm.

The first model is a single circuit transmission line; this transmission line requires at least two sets of measurements to estimate the line parameters, several cases were studied, these case studies are testing the proposed approach if it will still produce accurate results when some errors added to one set of measurement.

Based on case studies, the proposed method can efficiently handle synchronized and unsynchronized data. The case studies have demonstrated that the proposed method can yield highly accurate results.

Chapter 5

Short Transmission Line

5.1 Introduction

A short transmission is a line with 80 km or less in length. Due to the small line length and operating voltage shunt capacitance can be neglected. Hence the performance of short lines depends upon the series impedance ’resistance and inductance’. The short transmission line is usually presented by series impedance only where the shunt element can be neglected.

The short transmission line positive sequence can be presented as a simple series circuit, where the series impedance is lumped of the series resistance and inductance. The short transmission line characterizes are

- To avoid voltage variations in a power system network, we have to maintain the ratio of the voltage magnitude of the receiving end voltage to the magnitude of the ending end voltage within $0.95 \leq VS/VR \leq 1.05$.
- Maintain the phase shift angle difference δ in a transmission line typically be $\leq 30^o$; this difference keeps the power flows in the transmission line below the static stability limit.
- For short transmission line, there are some restrictions and limits can be high or less important in different circumstances.
  - Since the short transmission line considers only the resistance and inductance, where series reactance Xl is relatively small, then the heat

through the resistive is usually limited the power transferred through this line.

– For transmission lines that longer than short line operating at lagging power factors, the voltage drop across the line is usually the limiting factor.

– For transmission lines that longer than short line operating at leading power factors, the maximum phase shift angle δ can be the limiting factor.

The remainder of this chapter is organized as follows, section 5.2 shows the proposed method based on the single circuit transmission line. Section 5.3 shows the derivation of the proposed method when the double circuit of the transmission line is used. The results with discussion are presented in section 5.4. The conclusion is presented in section 5.5.

5.2 Short transmission line single Circuit

The short transmission line shown in figure 5-1 is operated at normal condition, the equivalent circuit is used to estimate the line parameters, and in short transmission line, the shunt admittance can be ignored.

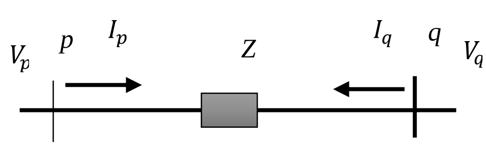

Figure 5-1 Short transmission line single circuit

By applying the Kirchhoff's Voltage Law to calculate the voltage at node q,

$$V_q = V_p - Z * I_p \tag{5.1}$$

The knowing parameters are $[V_p, V_q, I_p]$, and the unknowing variables are $[Z]$, by expanding the equation (5.1) for multiple sets of measurements as:

$$\begin{bmatrix} V_{p1} - V_{q1} \\ \vdots \\ V_{pn} - V_{qn} \end{bmatrix} = \begin{bmatrix} I_{p1} \\ \vdots \\ I_{pn} \end{bmatrix} [Z] \tag{5.2}$$

where n is the total number of measurements.

Since Z is given by

$$Z = R + jXL \tag{5.3}$$

From the equation (5.3) the line parameters are:

The series resistance= Real (Z)

Series inductance = Imag (Z)

By dividing the resistance and inductance by the length of the line, the results are in per unit of length.

5.3 Short transmission line double lines

Figure 5-2 shows a simple short transmission line. Z_1 and Z_2 are the total series impedances of line 1 and line 2 respectively. The shunt element can be ignored for short line. No matter whether the values of line impedances of the two lines are the same or different, the proposed method will yield accurate results.

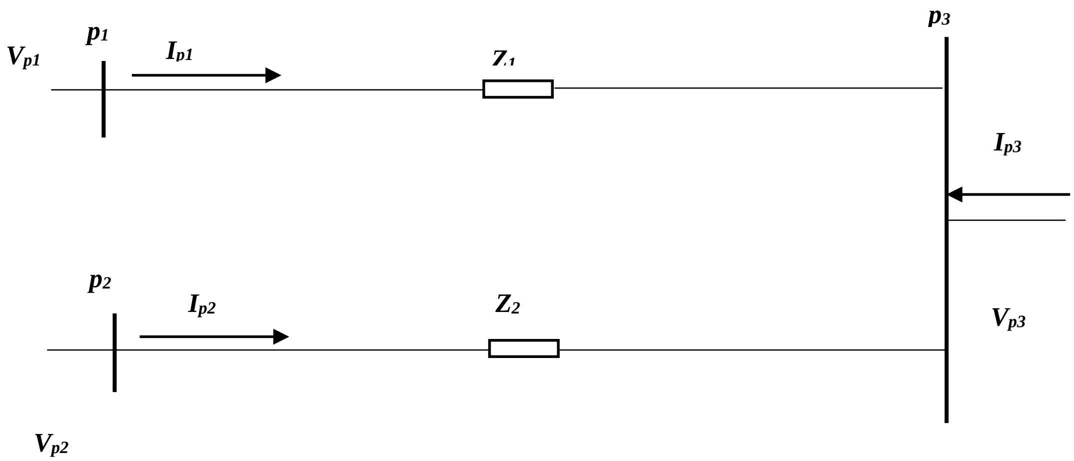

Figure 5-2 Short transmission line double circuits

The equivalent circuit of the short transmission line shown in figure 5-2 can be solved as a simple AC circuit as

The voltage at node p_3 according to the node p_1

$$V_{p3} = V_{p1} - Z_1 * I_{p1} \tag{5.4}$$

Then the voltage at p_3 referring to p_2

$$V_{p3} = V_{p2} - Z_2 * I_{p2} \tag{5.5}$$

The known values are [V_{p1}, $V_{p2,}$ I_{p1}, I_{p2}], and the unknown parameters are [Z_1, Z_2]. By eliminating the intermediate variables at bus p_3, equations (5.3) and (5.4) can be rewritten as:

$$V_{p1} - Z1 * I_{p1} = V_{p2} - Z2 * I_{p2} \tag{5.6}$$

Equation (5.6) is rearranged regarding to the unknown parameters as:

$$V_{p1} - V_{p2} = Z1 * I_{p1} - Z2 * I_{p2} \tag{5.7}$$

The equation (5.7) can be written in terms of unknown parameters as

$$[V_{p1} - V_{p2}] = [I_{p1} \qquad - I_{p2}] + \begin{bmatrix} Z_1 \\ Z_2 \end{bmatrix} \tag{5.8}$$

Where,

$$A = Z_1 \tag{5.9}$$

$$B = Z_2 \tag{5.10}$$

c, X vector is defined as

$$X = \begin{bmatrix} A \\ B \end{bmatrix} \tag{5.11}$$

There are two unknown variables [Z_1, Z_2], and to solve this equation, at least two sets of measurement are needed. The equation (5.8) can be expanded to any number of measurements that available as:

$$\begin{bmatrix} V_{p1i} - V_{p2i} \\ . \\ . \\ V_{p1N} - V_{p2N} \end{bmatrix} = \begin{bmatrix} I_{p1i} & - I_{p2i} \\ & . \\ & . \\ I_{p1N} & - I_{p2N} \end{bmatrix} * \begin{bmatrix} A \\ B \end{bmatrix} \tag{5.12}$$

where $i = 1, 2, \dots, N$ and N is the total number of measurements.

By using the linear least square method, the equation (5.8) can be solved using the equation below

$$U = H\, X \tag{5.13}$$

Where H is the two terminals currents, U is the voltages difference between the two nodes p_1 and p_2, and X the unknown variables vector. The solution to equation (5.13) is

$$X = (H^T\, H)^{-1}\ (H^T\, U) \tag{5.14}$$

The transmission line parameters for each circuit can be calculated in per unit of length as

- Line1
  - Series resistance = Real (A)/L
  - Series reactance = Image (A)/L

Where L is the line length, and all estimated parameters are in ohm per unit of length.

- Line 2
  - Series resistance = Real (B)/L2
  - Series reactance = Image (B)/L2

Where L2 is the line 2 length, and all estimated parameters are in ohm per unit of length.

5.4 Results and Discussion

The Matlab simulation, modeling and the three-phase sources that were connected to each end of the transmission line. The short transmission line model was implemented in the simulation to generate voltages and currents measurements by applying either multiple loads or changing the phase shift angle to get multiple sets of measurements. The transmission lines are assumed to be operating in normal condition, transposed and have either the same or different values for the series impedances whenever a double circuit is used.

5.4.1 Results for Short Line Single Circuit

The exact positive sequence of transmission line parameters are shown below. The developed algorithm is capable of estimating the line parameters using synchronized data.

- Series Resistance

$$R = 6.19303 \times 10^{-4} \text{ p.u./km}$$

➢ Series inductance

$$L = 1.46432 \times 10^{-3} \text{ p.u./km}$$

➢ Shunt Capacitance

$$C = 1.14016 \times 10^{-3} \text{ p.u./km}$$

By using four sets of measurement and applying the proposed method, the positive sequence of line parameters can be estimated as shown in table 5-1.

Table 5-1 Estimated posistive sequance line parameters based on short transmission line

Quantities	**1st set**	**2nd set**	**3rd set**	**4th set**
$\boldsymbol{V_p}$	0.995760+ 0.175598i	0.965959 + 0.239071i	0.935291+ 0.321545i	0.892378+ 0.493278i
$\boldsymbol{V_q}$	0.993315+ 0.175374i	0.978261 + 0.188589i	0.948253+ 0.271777i	0.916426 + 0.445919i
$\boldsymbol{I_p}$	0.022906 - 0.039316i	0.436986 + 0.324586i	0.427441 + 0.327970i	0.358922+ 0.425173i
Actual Values	R = 6.193032e-04 p.u		L = 1.464328e-3 p.u	
Estimated Parameters	R = 6.1868130e-04		L = 1.463976e-3 p.u	
Error	0.10%		0.02%	

Tables 5-2 and 5-3 are showing the estimated positive sequence of the transmission line parameter when the error is added to one set of measurements. Table 5-2 is testing the robustness of the proposed method when 2% of error is added to the second set of the voltage at terminal p. Table 5-3 is showing that the developed algorithm still produces an accurate estimation of positive sequence of the line parameters when 2% of error is added to the fourth set of the voltage at terminal q.

Table 5-2 Short transmission line with 2% error added to V_{p2} at terminal *p*

Quantities	1st set	2nd set	3rd set	4th set
V_p	0.995760+ 0.175598i	0.985278 + 0.243852i	0.935291+ 0.321545i	0.892378+ 0.493278i
V_q	0.993315+ 0.175374i	0.978261 + 0.188589i	0.948253+ 0.271777i	0.916426 + 0.445919i
I_p	0.022906 - 0.039316i	0.436986 + 0.324586i	0.427441 + 0.327970i	0.358922+ 0.425173i
Actual Values	R = 6.193032e-04 p.u		L = 1.464328e-3 p.u	
Estimated Parameters	R = 8.0411928e-04		L = 1.386394e-3 p.u	
Error	22.98%		5.32%	

Table 5-3 Short transmission line with 2% error added to V_{q4} at terminal *q*

Quantities	1st set	2nd set	3rd set	4th set
V_p	0.995760+ 0.175598i	0.965959 + 0.239071i	0.935291+ 0.321545i	0.892378+ 0.493278i
V_q	0.993315+ 0.175374i	0.978261 + 0.188589i	0.948253+ 0.271777i	0.934755 + 0.454837i
I_p	0.022906 - 0.039316i	0.436986 + 0.324586i	0.427441 + 0.327970i	0.358922+ 0.425173i
Actual Values	R = 6.193032e-04 p.u		L = 1.464328e-3 p.u	
Estimated Parameters	R = 4.263558e-04		L = 1.549175e-3 p.u	
Error	45.28 %		5.79%	

Table 5-4 shows the negative impact of the errors on current measurements; the current also may contain some errors due to reading or device errors range. The 2% of error has been added to the first set of the current measurement at the terminal *p*.

Table 5-4 Short transmission line with 2% error added to the I_{p1} at terminal p

Quantities	**1st set**	**2nd set**	**3rd set**	**4th set**
V_P	0.995760+ 0.175598i	0.965959 + 0.239071i	0.935291+ 0.321545i	0.892378+ 0.493278i
V_q	0.993315+ 0.175374i	0.978261 + 0.188589i	0.948253+ 0.271777i	0.916426 + 0.445919i
I_P	0.0233581 - 0.040102i	0.436986 + 0.324586i	0.427441 + 0.327970i	0.358922+ 0.425173i
Actual Values	R = 6.193032e-04 p.u		L = 1.464328e-3 p.u	
Estimated Parameters	R = 6.186412e-04		L = 1.463878e-3 p.u	
Error	0.10%		0.03%	

Table 5-5 exhibits the robustness of estimation method when 5% of error is added to the last set of the current measurement. The algorithm shows that the accurate result can still be obtained even with 5% of error.

Table 5-5 Short transmission line with 5% error added to the I_{p4} at terminal p

Quantities	**1st set**	**2nd set**	**3rd set**	**4th set**
V_p	0.995760+ 0.175598i	0.965959 + 0.239071i	0.935291+ 0.321545i	0.892378+ 0.493278i
V_q	0.993315+ 0.175374i	0.978261 + 0.188589i	0.948253+ 0.271777i	0.916426 + 0.445919i
I_p	0.022906 - 0.039316i	0.436986 + 0.324586i	0.427441 + 0.327970i	0.376868+ 0.4464325i
Actual Values	R = 6.193032e-04 p.u		L = 1.464328e-3 p.u	
Estimated Parameters	R = 6.078789e-04		L = 1.4 438415e-3 p.u	
Error	1.87%		1.76%	

5.4.2 Short Transmission Line Double Circuit

The short transmission line model was implemented in the simulation to generate the currents at different moments. The two short transmission lines are assumed to be operating at normal condition and have either the same or different values for the series impedances. The length of the transmission lines are 50 Km and 35 Km for line 1 and line 2 respectively. The exact transmission line parameters for both lines are the same values. The developed algorithm is capable of estimating the line parameters whether they are the same or different values.

Table 5-6 shows the estimated line parameters using the proposed approach that linearly estimates the transmission line parameters. By using two sets of measurements and developed methods, we can estimate the line parameters with highly accurate results as shown in the next tables.

Table 5-6 Estimated short transmission line parameters

Quantities	**First Set**	**Second Set**
$\boldsymbol{V_{p1}}$	0.98928 + 0.04388i	0.97828 + 0.13191i
$\boldsymbol{V_{p2}}$	0.99217 - 0.00703i	0.99380 + 0.03426i
$\boldsymbol{I_{P1}}$	0.60760 + 0.27000i	0.97316+ 0.52742i
$\boldsymbol{I_{p2}}$	0.04589 - 0.01959i	-0.11732 - 0.18775i
Line 1	R1= 0.00062147 p.u/km	L1= 0.00146204 p.u/km
Errors %	**0.34%**	**0.15%**
Line 2	R2 =0.00062325 p.u/ km	L2= 0.0014688 p.u/km
Errors %	**0.63%**	**0.30%**

Table 5-7 shows the estimated line parameters for short transmission lines when the error is added to one set of measurements in the current at terminal p_2. The results indicate that the developed algorithm is estimating the line parameters with high accuracy.

Table 5-7 Estimated short transmission line parameters with 2% Error on I_{p2}

Quantities	First Set	Second Set	Third Set
V_{p1}	0.98928 + 0.04388i	0.97828 + 0.13191i	0.943921+ 0.298625i
V_{p2}	0.99217 - 0.00703i	0.99380 + 0.03426i	0.985718+ 0.207396i
I_{P1}	0.60760 + 0.27000i	0.97316+ 0.52742i	0.826334+ 0.739479i
I_{p2}	0.04589 - 0.01959i	-0.11732 - 0.18775i	-0.033866 - 0.27683i
Line 1	R1= 0.00062261 p.u/km	L1= 0.00146269 p.u/km	
Errors %	**0.5322 %**	**0.11 %**	
Line 2	R2 = 0.00060305p.u/ km	L2= 0.00146145 p.u/km	
Errors %	**2.69 %**	**0.19 %**	

Table 5-8 Estimated transmission line parameters when over-length is used

Quantities	First Set	Second set	Third set	Fourth set
V_{p1}	1.07491+ 0.09002i	0.99455+ 0.24845i	0.94712+ 0.41357i	0.84968+ 0.56185i
I_{P1}	0.36474+ 0.31584i	0.38351+ 0.39437i	0.34755+ 0.48135i	0.23243+ 0.55138i
V_{p2}	1.01864+ 0.01909i	1.00496+ 0.18401i	0.97465+ 0.33824i	0.89521+ 0.50553i
I_{p2}	-0.12758+ 0.05975i	-0.09284+ 0.08865i	-0.14504+ 0.01225i	-0.06684+ 0.00162i
Line 1	SeriesResistance:2.83643e-04 p.u/km		Series inductance : 0.00335433 p.u/km	
Line 2	Series Resistance: 0.0088310 p.u/km		Series inductance : 0.0012715 p.u/km	

Table 5-8 indicates that the developed algorithm cannot determine the line parameters accurately. The estimated parameters for the second line is supposed to be a short transmission line.

5.5 Conclusion

The two short transmission lines configuration are employed in this chapter. These configurations are used to estimate the positive sequence on the short transmission line under the normal conditions by using the linear least square method.

The first case study was about the short transmission line single circuit. The proposed method illustrates that the approach yields highly accurate estimated parameters; to test the linear method against the negative impact such as an error that the measurements may carry. The proposed approach is still shown as an accurate estimation even with errors.

The double circuit transmission line method is developed in section 5.4.2. This method is using two nodes sharing the same end node. These transmission lines can have either the same or different line parameters. The proposed algorithm can handle both cases. Several cases were studied to test the algorithm against the negative impact, and these cases indicated that every line length has to use its proper algorithm.

Chapter 6

Temperature Effects

6.1 Introduction

Today, due to the increase of reliable and safe operations, the traditional methods are not capable of handling the short-term changes in line parameters, which may occur due to Joule heating and ambient temperature variation. These days, the most desirable method is the one that can estimate the line parameters online and in real time from PMU's data, using the measurements of voltage and current at both ends. The PMU's are usually installed at the substations. [27].

This chapter only considers the series resistance as an unknown parameter due to temperature change. Since the variation of temperature will only affect the resistance, the series reactance and shunt capacitance can be treated as a known variable. The series reactance and shunt capacitance can be estimated at normal conditions using the methods described in [7], to track the variation of the value of series resistance due to temperature changes. The developed method can accurately estimate the resistance values and should be able to deal with the possible errors that may occur while taking the PMU readings or manufacture's errors range.

The idea of this chapter is to use only one set of measurement. By reducing the unknown variable, we can reduce the required voltage and current measurements. Therefore, the voltages at both terminal are required and the current at one end.

This chapter is structured as follows: section 6.2 shows the derivation of the proposed method for the long transmission line; section 6.3 represents the medium transmission that is mathematically modeled to be used to estimate the series resistance. The methods for estimating the series resistance of short transmission line is shown in section 6.4. Section 6.5 illustrates the case studies of simulated transmission lines; and section 6.5 presents a discussion of the obtained results, followed by the conclusions.

6.2 Long Transmission Line

The long transmission line shown in figure (6-1), this transmission line is assumed to be operated under normal operation, transposed, and balanced three phase. The series impedance in a long line is defined by hyperbolic function. Thus all transmission line branches will be affected even the shunt admittance.

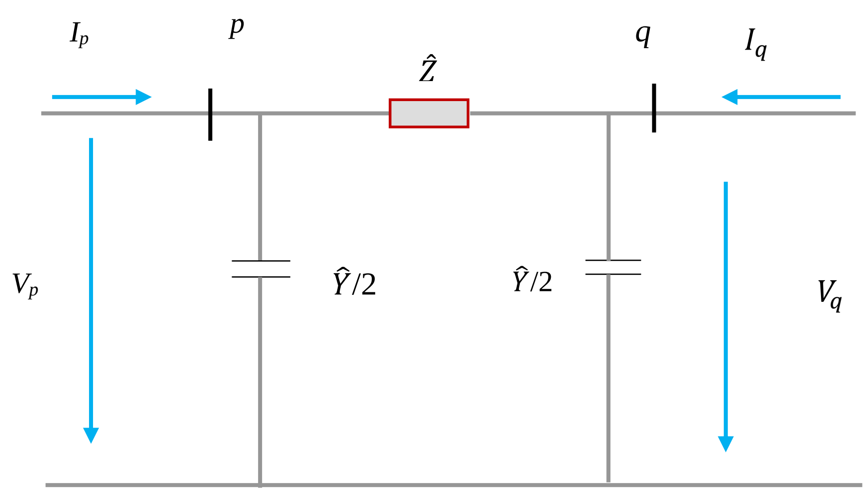

Figure 6-1 Equivalent circuit of a long transmission line

Assuming perfect synchronization is considered. The following equation can be obtained

$$I_p = \left(\hat{Y} + (1/\hat{Z})\right)V_p - (1/\hat{Z})V_q \tag{6.1}$$

Since the long transmission line is considered, then the parameters shown in equation (6.1) are the distributed transmission line parameters, to calculate the series resistance the following equations are used

$$\hat{Z} = Zc\ sinh(\gamma l) \tag{6.2}$$

$$\hat{Y} = \ tanh(\gamma l/2)/Zc \tag{6.3}$$

where

$$Zc = \ \sqrt{z/y} \tag{6.4}$$

$$\gamma = \sqrt{z * y} \tag{6.5}$$

The series impedance is

$$z = R + jxl \tag{6.6}$$

Rewrite the equations (6.4) and (6.5) as

$$Zc = \ \sqrt{(R + jxl)/y} \tag{6.7}$$

$$\gamma = \sqrt{(R + jxl) * y} \tag{6.8}$$

Substitute the equations (6.2) to (6.5) into equation (6.1); the known variables are [I_p, V_p, V_q, y, xl].

$$\begin{aligned} I_p = \big(\ tanh\big((\sqrt{(R + jxl) * y})l/2\big)/(\sqrt{(R + jxl)/y}) \\ + (1/(\sqrt{(R + jxl)/y})\ sinh\big((\sqrt{(R + jxl) * y})l\big)\big)\big)V_p \\ - (1/((\sqrt{(R + jxl)/y})\ sinh\big((\sqrt{(R + jxl) * y})l\big)))V_q \end{aligned} \tag{6.9}$$

There is only one unknown value in equation (6.7) which is series resistance R, solve the equation (6.7) to get the value of the series resistance.

If there is potential synchronization error is considered then δ is presented as an unsynchronization angle. The equation (6.1) can be written as

$$I_p = \left(\hat{Y} + (1/\hat{Z})\right)V_p - (1/\hat{Z})V_q e^{i\delta} \qquad (6.10)$$

$$I_q e^{i\delta} = \left(\hat{Y} + (1/\hat{Z})\right)V_q e^{i\delta} - (1/\hat{Z})V_p \qquad (6.11)$$

By substitute the equations (6.2) to (6.5) into equation (6.10) and (6.11). The known variables are [I_p, V_p, V_q, I_q, y, xl], the only unknown quantities are [R, δ]

$$\begin{aligned} I_p = \Big(& tanh\left((\sqrt{(R+jxl)*y})l/2\right)/(\sqrt{(R+jxl)/y}) \\ & + (1/(\sqrt{(R+jxl)/y})\ sinh\left((\sqrt{(R+jxl)*y})l\right))\Big)V_p \qquad (6.12) \\ & - (1/((\sqrt{(R+jxl)/y})\ sinh\left((\sqrt{(R+jxl)*y})l\right)))V_q e^{i\delta} \end{aligned}$$

$$\begin{aligned} I_q e^{i\delta} = \Big(& tanh\left((\sqrt{(R+jxl)*y})l/2\right)/(\sqrt{(R+jxl)/y}) \\ & + (1/(\sqrt{(R+jxl)/y})\ sinh\left((\sqrt{(R+jxl)*y})l\right))\Big)V_q e^{i\delta} \qquad (6.13) \\ & - (1/((\sqrt{(R+jxl)/y})\ sinh\left((\sqrt{(R+jxl)*y})l\right)))V_p \end{aligned}$$

We have two equations (6.12) and (6.13) and two unknown values, solve these two equations to obtain the unknown values.

6.3 Medium Line

The medium transmission line shown in figure (6.1) is operated at normal condition. The equivalent circuit is used to estimate the line parameters first. After getting the estimated line parameters, which are series resistance and series inductance, and due to the change of ambient temperature, only the series resistance will be affected. Therefore, the series inductance and shunt capacitance can be treated as known parameters. Based on the previous method of estimating the line parameters linearly, the series resistance can be estimated using the same procedures. Assuming unsynchronized data are used. Introducing a new variable δ. The unsynchronized angle will be zero if perfect synchronized data are used.

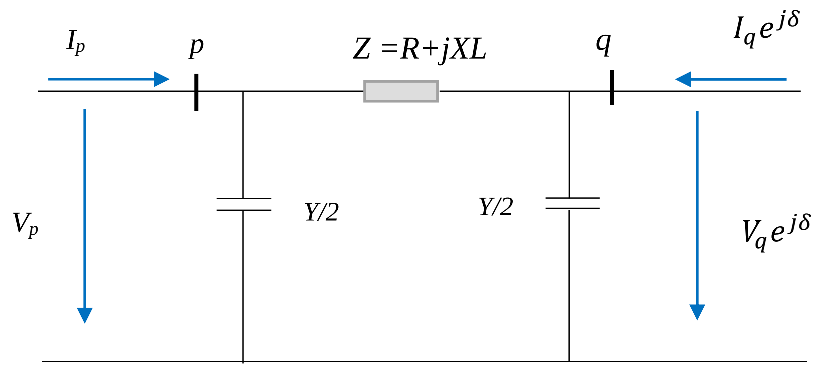

Figure 6-2 Medium transmission line

By using Kirchhoff's voltage and current laws, the circuit equations are

$$V_q e^{j\delta} = V_p - \left(I_p - \frac{Y}{2} V_p\right) Z \tag{6.14}$$

$$I_q e^{j\delta} - \left(\frac{Y}{2}\right) V_q \, e^{j\delta} - \left(\frac{Y}{2}\right) V_p + I_p = 0 \tag{6.15}$$

Since the known variables are $[V_q,\ V_p,\ I_p, I_q, Y]$, and the unknown parameter is δ , by rearranging the equation (6.11), the unsynchronization angle can be calculated using the equation (6.11) as follows:

$$e^{j\delta} = (I_p - \left(\frac{Y}{2}\right) V_p) \,/ (I_q - \left(\frac{Y}{2}\right) V_q) \tag{6.16}$$

The known quantities are [V_p, I_p, V_q, δ, xl, Y], and the unknown variable is [R]. Solve the equation (6.10) to calculate the series resistance.

$$V_q e^{j\delta} = V_p + \frac{Y}{2}\, V_p\, Z \; - I_p\, Z \tag{6.17}$$

$$[V_q e^{j\delta} - V_p] = [\frac{Y}{2}\, V_p \; - I_p]\,(R + jXl) \tag{6.18}$$

$$R = \frac{\left[V_p - V_q e^{j\delta}\right]}{\left[\, I_p - \frac{Y}{2}\, V_p \,\right]} - jXl \tag{6.19}$$

6.3.1 Medium Transmission Line double circuit

Figure 6-2 represents the medium transmission line with three-end nodes. This figure used to develop a new algorithm to estimate the positive sequence of series impedance when the ambient temperature is changed.

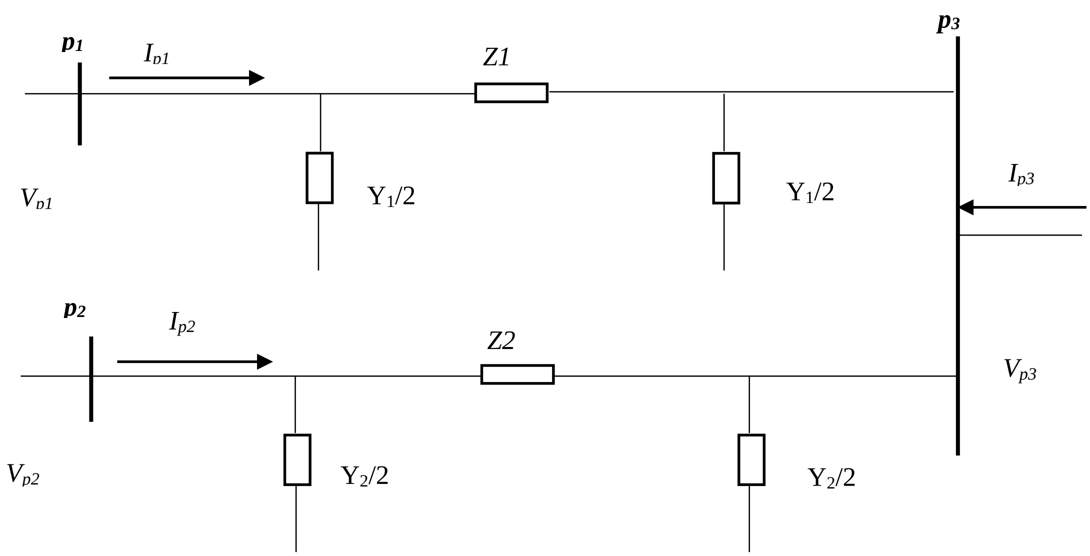

Figure 6-3 Doule circuit medium transmission line

Based on figure 6-2, assuming the synchro-phasors data are adopted, the following equations can be obtained:

$$V_{p3} = V_{p1} - \left(I_{p1} - \frac{Y_1}{2}\, V_{p1}\right) Z_1 \tag{6.20}$$

$$V_{p3} = V_{p2} - \left(I_{p2} - \frac{Y_2}{2} V_{p2}\right) Z_2 \tag{6.21}$$

Since the known variables are $[V_{p1}, V_{p2}, V_{p3}, I_{p1}, I_{p2}, Y_1, Y_2, X_1, X_2]$, the only unknown parameters are $[R_1, R_2]$, by rearranging the equations (6.14) and (6.15). The series resistances can be simply calculated as follows:

$$R_1 = \frac{V_{p1} - V_{p3}}{\left(I_{p1} - \frac{Y_1}{2} V_{p1}\right)} - jXl_1 \tag{6.22}$$

$$R_2 = \frac{V_{p2} - V_{p3}}{\left(I_{p2} - \frac{Y_2}{2} V_{p2}\right)} - jXl_2 \tag{6.23}$$

6.4 Short Transmission Line

The short transmission line shown in figure (6.3) is operated at normal condition. First, the equivalent circuit is used to estimate the line parameters as shown in chapter 5. After getting the estimated line parameters, which are series resistance and series inductance, in a short transmission line, the shunt admittance ignored, and due to change of ambient temperature, the series resistance will only be affected. Therefore, the series inductance can be treated as a known parameter. Based on the previous method of estimating the line parameters linearly, the series resistance can be estimated using the same procedures.

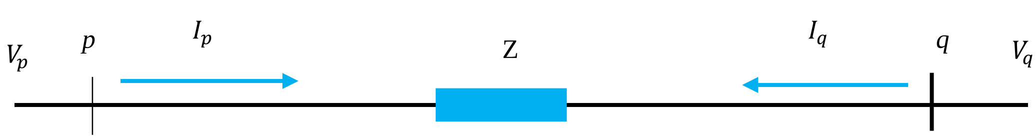

Figure 6-4 Short transmission line single line

Based on figure 6-3, assuming the synchronous phasors are adopted, the following equations can be obtained:

$$V_q = V_p - Z * I_p \qquad (6.24)$$

where

$$Z = R + jxl \qquad (6.25)$$

The known parameters are $[V_p\ , V_{q,}\ I_p, xl]$, and the unknown variable is [R]. The equation (6.18) needs to be rearranged in terms of the unknown variables, so that yields

$$Z\ I_p = V_p - V_q \qquad (6.26)$$

The series resistance can be calculated as

$$R = \left(\frac{V_p - V_q}{I_p}\right) - jXl \qquad (6.27)$$

Assuming unsynchronized data are adopted. Then the figure 6-5 can be represented as

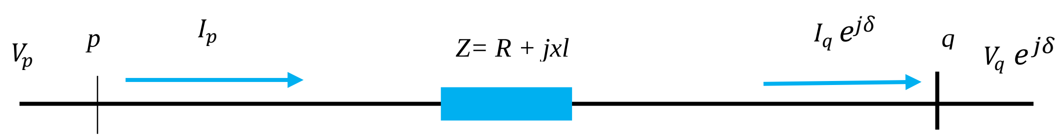

Figure 6-6 Short transmission line with unsynchronization angle adopted

By solving a simple AC circuit, the following equations can be obtained.

$$V_q e^{j\delta} = V_p - Z * I_p \qquad 6.28)$$

The unsynchronization angle can be calculated using the next equation

$$e^{j\delta} = I_p / I_q \qquad 6.29)$$

The known values are $[V_q, V_p, I_p$, xl, I_q].The only unknown value is the series resistance, solving equation (6.22) to obtain the value of series resistance in per unit as follows.

$$R = (V_q e^{j\delta} - V_p - I_p * jxl)/I_p \qquad 6.30)$$

6.5 Results

The Matlab simulation, SimPower tool, and the three-phase sources were connected to each end of the transmission line. The short transmission line model was implemented in the simulation to generate voltages and currents. The transmission lines are assumed to be operating in normal condition, transposed, and have either same or different values for the series impedances whenever a double circuit is used.

6.5.1 Long Transmission Line

The estimated series inductance and shunt capacitance in chapter 3 are used in this section as known parameters. Table 6-1 shows the estimated series resistance in per unit of length.

Table 6-1 Estimated resistance of long transmission line when synchronized data are used

Quantities	**Values P.U**
V_p	1.05300 - 0.02268i
V_q	1.10788 - 0.052780i
I_p	0.00749 + 0.31028i
Estimated R	7.978244199264177e-04
Actual Value	8.050939000000000e-04
Error	0.91%

Table 6-2 Estimated resistance of long transmission line when unsynchronized data are used

Quantities	**Values P.U**
V_p	0.993922 + 0.140065i
V_q	0.9499553 - 0.193174i
I_p	0.017586 + 0.006672i
I_q	0.027750 + 0.221128i
UnSync Angl	20.62^o
Estimated R	0.000618124
Actual Value	0.000619303

6.5.2 Medium Transmission Line Single Circuit

The actual estimated line parameters such as series inductance and shunt capacitance are used from chapter 4. These parameters are in per unit of length. Table 6-2 shows the estimated positive sequence of the medium transmission line using one set of measurements with estimated line inductance and capacitance using the developed method in chapter 4.

Table 6-3 Medium transmission line single line with synchronized data

Quantities	Values P.U
V_p	1.050623 + 0.165500i
V_q	1.084189 + 0.153868i
I_p	-0.029209 + 0.237103i
Estimated R	6.170365e-04
Actual Value	6.19303e-04
Error	0.36%

Tables 6-4 and 6-5 are testing the robustness of the method with negative impacts such as error due to personal reading or device range errors. The 2% of errors have been added to the voltage at both ends randomly; the developed method shows an accurate result for estimating the positive sequence of the series resistance.

Table 6-4 Medium transmission line length with 2% error on V_p

Quantities	Values P.U
V_p	1.071636 + 0.168810i
V_q	1.084189 + 0.153868i
I_p	-0.029209 + 0.237103i
Estimated R	6.922399e-04
Actual Value	6.19303e-04
Error	11.77%

Table 6-5 Medium transmission line length with 2% error on V_q

Quantities	Values P.U
V_p	1.050623 + 0.165500i
V_q	1.105873 + 0.156946i
I_p	-0.029209 + 0.237103i
Estimated R	5.677124e-04
Actual Value	6.19303e-04
Error	8.33%

The effect of the errors that the measurements may carry has been evaluated on both lines as shown in the next two tables. Tables 6-6 and 6-7 are testing the method by adding errors to the current measurements. The errors are added to one set of current's measurements, and to the currents at both ends.

Table 6-6 Medium transmission line length with *2*% error on current I_p

Quantities	Values P.U
V_p	1.050623 + 0.165500i
V_q	1.084189 + 0.153868i
I_p	-0.029793 + 0.241845i
Estimated R	5.9477968e-04
Actual Value	6.19303e-04
Error	3.95%

Table 6-7 Medium transmission line length with 5% error on current I_p

Quantities	Values P.U
V_p	1.050623 + 0.165500i
V_q	1.084189 + 0.153868i
I_p	-0.030669 + 0.248958i
Estimated Resistance	5.642307e-04
Actual Value	6.19303e-04
Error	8.89%

Table 6-8 Medium transmission line single line with unsynchronized data

Quantities	Values P.U
V_p	1.036519 + 0.238385i
V_q	1.067022+ 0.183993i
I_p	0.029018 + 0.237126i
I_q	-0.059285 - 0.115613i
Estimated Resistance	6.19302e-04
UnSync Angle	2.62^o
Error	1e-4 %

6.5.3 Medium Transmission Line Double Circuit

The double circuit of the medium transmission line is used to evaluate the developed method, and multiple case studies are adopted in each case. The multiple error levels are added to one set of measurements each time. The last three rows in each of the following tables are representing estimated series resistance with errors added to voltage or current measurements as specified. Tables 6-9 and 6-10 represent the estimated line resistance for the first line (p_1-p_3) when the errors are added to the voltage and current at p_1 terminal: all results are sorted in table 6-9.

Table 6-9 Estimated first line resistance in P.U of length with errors on V_{p1}

Quantities	Values P.U	Estimated R	Error
V_{p1}	1.019917 + 0.166133i	R1=5.855903e-04	5.44%
V_{p3}	1.038982 + 0.160674i		
I_{p1}	-0.025534 + 0.179057i		
V_{p1}.+5%Error	1.070913 + 0.174440i	R1= 9.15866e-04	47.88%
V_{p1}.+3%Error	1.050514 + 0.171117i	R1= 7.698846e-04	24.31%
V_{p1}.+1%Error	1.030116 + 0.167794i	R1 =6.428936e-04	3.80%

Table 6-10 Estimated first line resistance in P.U of length with errors on I_{p1}

Quantities	Values P.U	Estimated R	Error
V_{p1}	1.019917 + 0.166133i	R1=5.855903e-04	5.44%
V_{p3}	1.038982 + 0.160674i		
I_{p1}	-0.025534 + 0.179057i		
I_{p1}.+5%Error	-0.026810 + 0.188010i	R1=5.1834423e-04	16.30%
I_{p1}.+3%Error	-0.026300 + 0.184429i	R1= 5.433188e-04	12.26%
I_{p1}.+1%Error	-0.025789 + 0.180848i	R1 =5.707951e-04	7.83%

Tables 6-11 and 6-12 represent the estimated line resistance for the first line (p_2-p_3) when the errors are added to the voltage and current at p_2 terminal.

Table 6-11 Estimated second line resistance in P.U of length with errors on V_{p2}

Quantities	**Values P.U**	**Estimated R**	**Error**
V_{p2}	1.019522 + 0.167362i	R2= 7.982347e-04	0.85%
V_{p3}	1.038982 + 0.160674i		
I_{p2}	-0.035476 + 0.182596i		
V_{p2}**.+5%Error**	1.070498 + 0.175730i	R2= 6.141560e-04	23.71%
V_{p2}**.+3%Error**	1.050107 + 0.172383i	R2= 6.917263e-04	14.08%
V_{p2}**.+1%Error**	1.029717+ 0.169035i	R2 = 7.639798e-04	5.10%

Table 6-12 Estimated first line resistance in P.U of length with errors on I_{p2}

Quantities	**Values P.U**	**Estimated R**	**Error**
V_{p2}	1.019522 + 0.167362i	R2= 7.982347e-04	0.85%
V_{p3}	1.038982 + 0.160674i		
I_{p2}	-0.035476 + 0.182596i		
I_{p2}**.+5%Error**	-0.037250 + 0.191726i	R2= 7.298240e-04	9.34%
I_{p2}**.+3%Error**	-0.036540 + 0.188074i	R2= 7.557337e-04	6.13%
I_{p2}**.+1%Error**	-0.035831+ 0.184422i	R2 = 7.835473e-04	2.67%

Table 6-13 examines the proposed approach when errors are added to the voltage at terminal *p3*. The errors on the voltage at p_3 will affect the series resistance on both lines, and the last three rows present the results with a range of errors from 1% to 5% of errors added to one set of measurements and the two lines' estimated resistance.

Table 6-13 Estimated second line resistance in P.U of length with errors on V_{p3}

Quantities	Values P.U	Estimated R	Error
V_{p1}	1.019917 + 0.166133i	R1=5.855903e-04	5.44%
V_{p2}	1.019522 + 0.167362i		
V_{p3}	+ 0.160674i	R2= 7.982347e-04	0.85%
I_{p1}	-0.025534 + 0.179057i		
I_{p2}	-0.035476 + 0.182596i		
V_{p3}.+5%Error	1.090931 + 0.168707i	R1=5.855903e-04 R2= 1.0413163e-03	37.92% 29.340
V_{p3}.+3%Error	1.059762+ 0.163887i	R1= 5.051324e-04 R2= 8.954674e-04	18.43% 11.22%
V_{p3}.+1%Error	1.049372 + 0.162280i	R1= 5.453613e-04 R2= 8.468511e-04	11.93% 5.18%

6.5.4 Short transmission line

Table 6-14 illustrates the estimated series resistance for the short transmission line using the estimated inductance in chapter 5. The estimated resistance shows that the method gives an accurate result.

Table 6-14 Estimated line resistance in P.U of length for short transmission line

Quantities	Values P.U
V_p	0.995767 + 0.175637i
V_q	0.991460 + 0.175085i
I_p	0.022900 - 0.039318i
Estimated Resistance	6.19288e-04
Actual Value	6.19303e-04
Error	0.00%

Table 6-15 exhibits the estimated positive sequence of series resistance for the short transmission line when errors at 1%, 2%, and 5% are added to the voltage at the sending end node. In these cases, the developed method cannot produce an accurate result as shown in the next table.

Table 6-15 Estimated line resistance in P.U of length with errors on V_p

Quantities	Values P.U	Estimated Resistance	Error
V_p	0.995767 + 0.175637i	6.19288e-04	0.00%
V_q	0.991460 + 0.175085i		
I_p	0.022900 - 0.039318i		
V_p. **5% Error**	1.04555 + 0.184419i	7.472678e-04	1.03e+03%
V_p. **2% Error**	1.015683 + 0.179150i	0.003178877170630	4.13e+02%
V_p. **1% Error**	1.005725 + 0.177394i	0.001899082774173	2.06e+02%
V_p. **0.1% Error**	0.996763 + 0.175813i	0.007018260360000	20.66%

Table 6-16 represents the results of the short transmission line when errors are added to the receiving end node q. The developed algorithm can give an accurate result for the series resistance estimation even when 5% of error is added. All estimated results are sorted in the last three rows in table 6-16.

Table 6-16 Estimated line resistance in P.U of length with errors on V_q

Quantities	Values P.U	Estimated Resistance	Error
V_p	0.995767 + 0.175637i	6.19288e-04	0.02%
V_q	0.991460 + 0.175085i		
I_p	0.022900 - 0.039318i		
V_q. 5% Error	0.024045 - 0.041284i	0.0057487	1.02e+03%
V_q. 2% Error	0.023358 - 0.040104i	0.0019279	4.11e+02%
V_q. 1% Error	0.023129 - 0.039711i	4.919282e-04	20.56 %
V_q. 0.1% Error	0.992451 + 0.1752606i	6.543131e-04	2.056%

The errors were added to the measurements by varying the error from 0.1% to 5% on the current as shown in the next table. The estimated resistance is sorted in the third column in per unit of length.

Table 6-17 Estimated line resistance in P.U of length with errors on I_p

Quantities	Values P.U	Estimated Resistance	Error
V_p	0.995767 + 0.175637i	6.19288e-04	0.02%
V_q	0.991460 + 0.175085i		
I_p	0.022900 - 0.039318i		
I_p. 5% Error	0.024045 - 0.041284i	5.897984e-04	4.76%
I_p. 2% Error	0.023358 - 0.040104i	6.07145e-04	1.96%
I_p. 1% Error	0.023129 - 0.039711i	6.13156e-04	0.99%
I_p. 0.1% Error	0.022923 - 0.039357i	6.186698e-04	0.10 %

Table 6-18 yields a result for an estimated positive sequence of short transmission line resistance when unsynchronized data are used. The developed algorithm can be used with synchronized data, and the unsynchronized angle will yield zero degree.

Table 6-18 Estimated short line resistance in P.U using unsynchronized data

Quantities	Values P.U
V_p	1.00234 + 0.052906i
V_q	1.057006 - 0.637575i
I_p	0.0180089 + 0.005429i
Iq	0.018678 + 0.002220i
Unsync Angle	9.98^o
Estimated Resistance	6.193031e-04
Actual Value	6.193030e-04
Error	0.00%

6.6 Conclusion

The ambient temperature may vary during the day, and this variation causes a change in line resistance. This chapter applies the linear estimation method in chapters 4 and 5 to estimate the positive sequence line parameters for medium and short lines. Since the temperature is only affecting the series resistance. Therefore, the series inductance and shunt capacitance remain the same values.

The idea in chapter 6 is to use the estimated inductance and capacitance as known parameters to estimate the series resistance; this makes the estimation method more simple by just collecting one set of measurements for the voltages and currents at both terminals from PMU's.

According to the results and case studies, the proposed method examines the negative impact of the errors on the measurements by adding errors to voltage and current measurements and applying the proposed approach. The results indicate that the proposed approach is more sensitive to errors on voltages than currents.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

The power transmission system is highly required in delivering electricity from one terminal to another. Safety and reliability are important factors for power system operation. Thus numerous power devices, programs, and research have been improved and developed. These research, programs, and devices require accurate transmission line parameters, including series resistance, series inductance, and shunt capacitance. Furthermore, the line sequence of impedance and lines' phase type are also important for power system analysis. The accuracy of these inputs plays a critical role in the power system networks.

Numerous studies of estimating transmission lines parameters have been developed. The most studied method is a non-linear method which uses the iteration and takes time to converge, and others are working off-line, and thus these methods cannot track the demand for power system control and operation. Some algorithms can work online; these algorithms are using Newton Raphson method, which takes time to provide the system with the accurate results. Newton Raphson method depends on the starting point to be able to estimate the line parameters accurately and uses less time to converge. Although, it is important to develop an effective and reliable method, and this method can accurately estimate the transmission line parameters, work online, and useless time.

The dissertation presents an online algorithm that linearly estimates the positive-sequence parameters of transmission lines. The proposed approach utilizes two terminal synchronized or unsynchronized measurements including voltages and currents that are taken at different time moments. The voltage and current measurements are measured by PMU's devices that installed at different terminals or substations; multiple transmission line configurations are modeled to be implemented in the developed method.

In this dissertation, an equivalent distributed PI circuit is used to model a long transmission line, so the shunt capacitances are accurately modeled. The two types of log transmission line circuits are used, the first circuit is a single circuit transmission line. The second circuit is double transmission lines with three nodes. A different set of measurements were used to accurately and linearly estimate the transmission line parameters. Several case studies were studied, the case studies indicate that the developed method has achieved accurate results. The linear method is technically sound and more computationally efficient than existing nonlinear methods.

Likewise, the medium transmission line was modeled and studied. The medium transmission line little easier than long line because it does not use the hyperbolic functions, the nominal PI circuit and two transmission line configurations were used to model the medium line. The developed algorithm was examined to ensure that the method provides accurate results during up normal conditions such as errors in measurements.

The short transmission line also was modeled, and different models of the short line were implemented to developed line estimation method. Several case studies were examined. The improving of robustness and accuracy of this method were studied by adding some errors to the measurements and detecting the unsynchronization error. Based on the results, the on-line linear method can produce an accurate on-line estimation of transmission line parameters.

The temperature effect was studied based on the conductor characteristics and relationship between line parameters and temperature. Since the linear method is used to estimate the line parameters in chapters 3, 4 and 5. These methods show accurate results for the parameters. The estimation method uses the estimated line parameters (series inductance and shunt capacitance) a known variable to estimate the series resistance, and this can be easily done using the developed method. Estimation result shows that the developed algorithm produced an accurate result for the series resistance and shown the effectiveness and reliability of the developed method.

In the end, the linear least square method is a method that can estimate the line parameters with high accuracy in less time.

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Vita

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